ZKFault: Fault Attack Analysis on Zero-Knowledge Based Post-Quantum Digital Signature Schemes

Puja Mondal, Supriya Adhikary, Suparna Kundu, and Angshuman Karmakar

Asiacrypt 2024, Kolkata, India

NIST's Additional Digital Signature

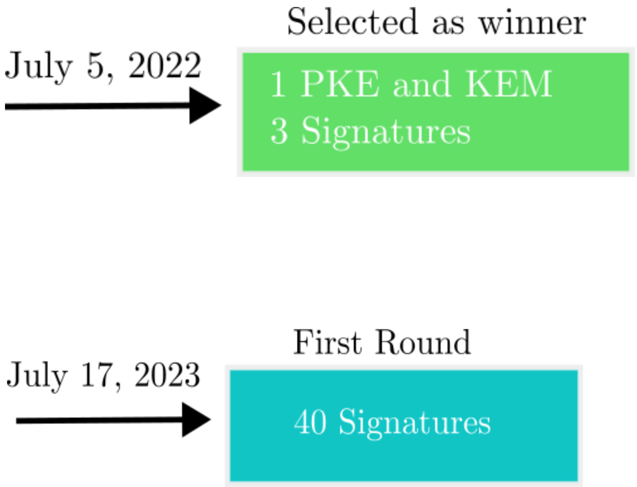
July 5, 2022

Selected as winner

1 PKE and KEM
3 Signatures

PKE and KEM	Signatures
CRYSTALS-Kyber	CRYSTALS-Dilithium FALCON SPHINCS+

NIST's Additional Digital Signature



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July 17, 2023

First Round

40 Signatures

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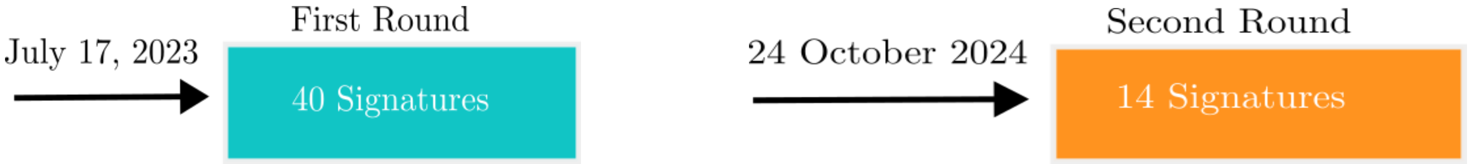

First Round

July 17, 2023

40 Signatures

Second Round

24 October 2024

14 Signatures

CROSS **FEAST** **HAWK** **LESS** **MAYO** **Mirath** **MQOM**

PERK **QR-UOV** **RYDE** **SDitH** **SNOVA** **SQIsign** **UOV**

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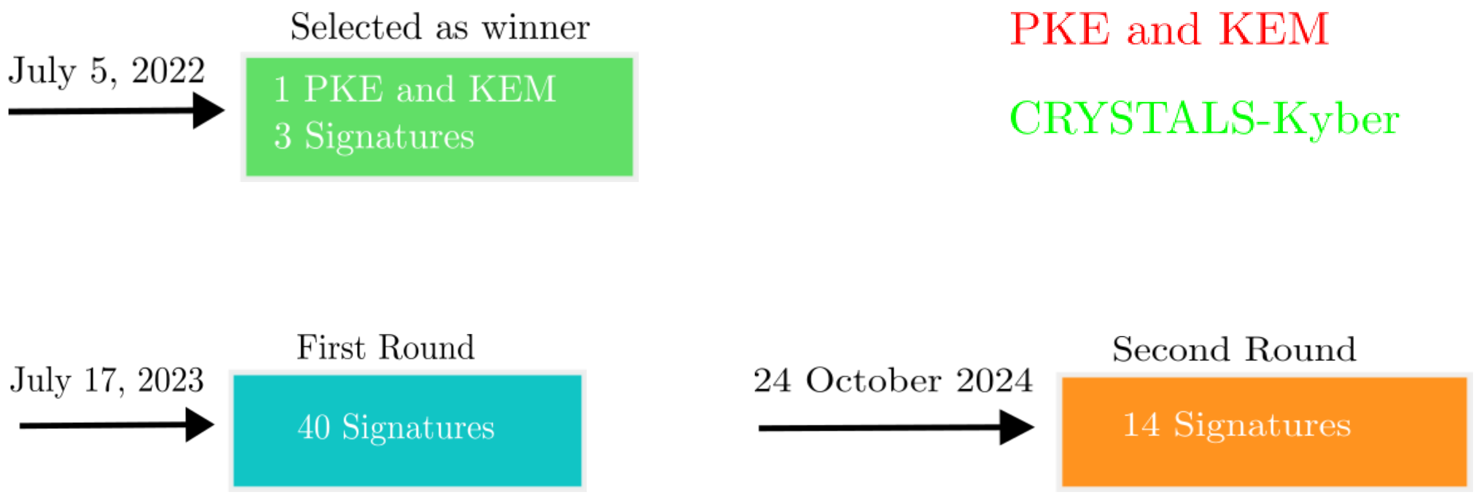

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✓			✓			
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Interactive-Zero-Knowledge (ZK) Framework

Prover

Verifier

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Public-info
Secret-info

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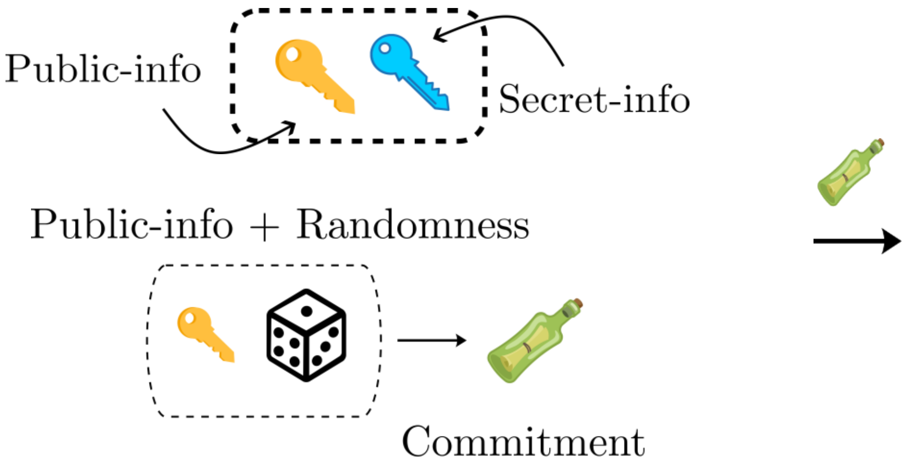


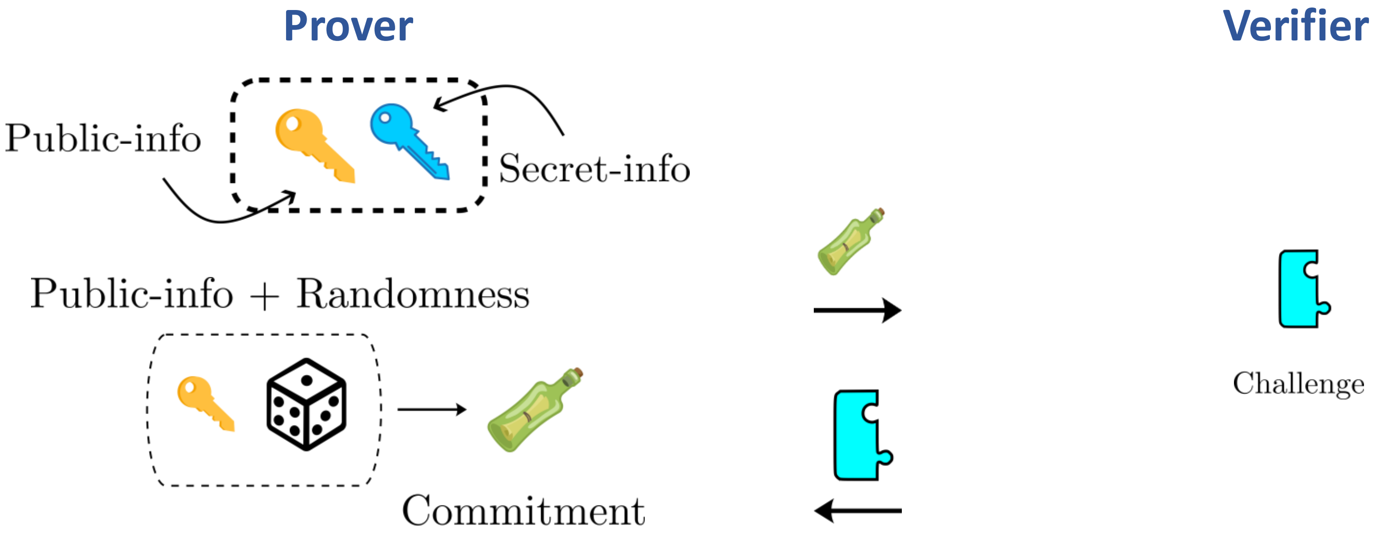
Public-info

Secret-info

Public-info + Randomness

Commitment

Interactive-Zero-Knowledge (ZK) Framework



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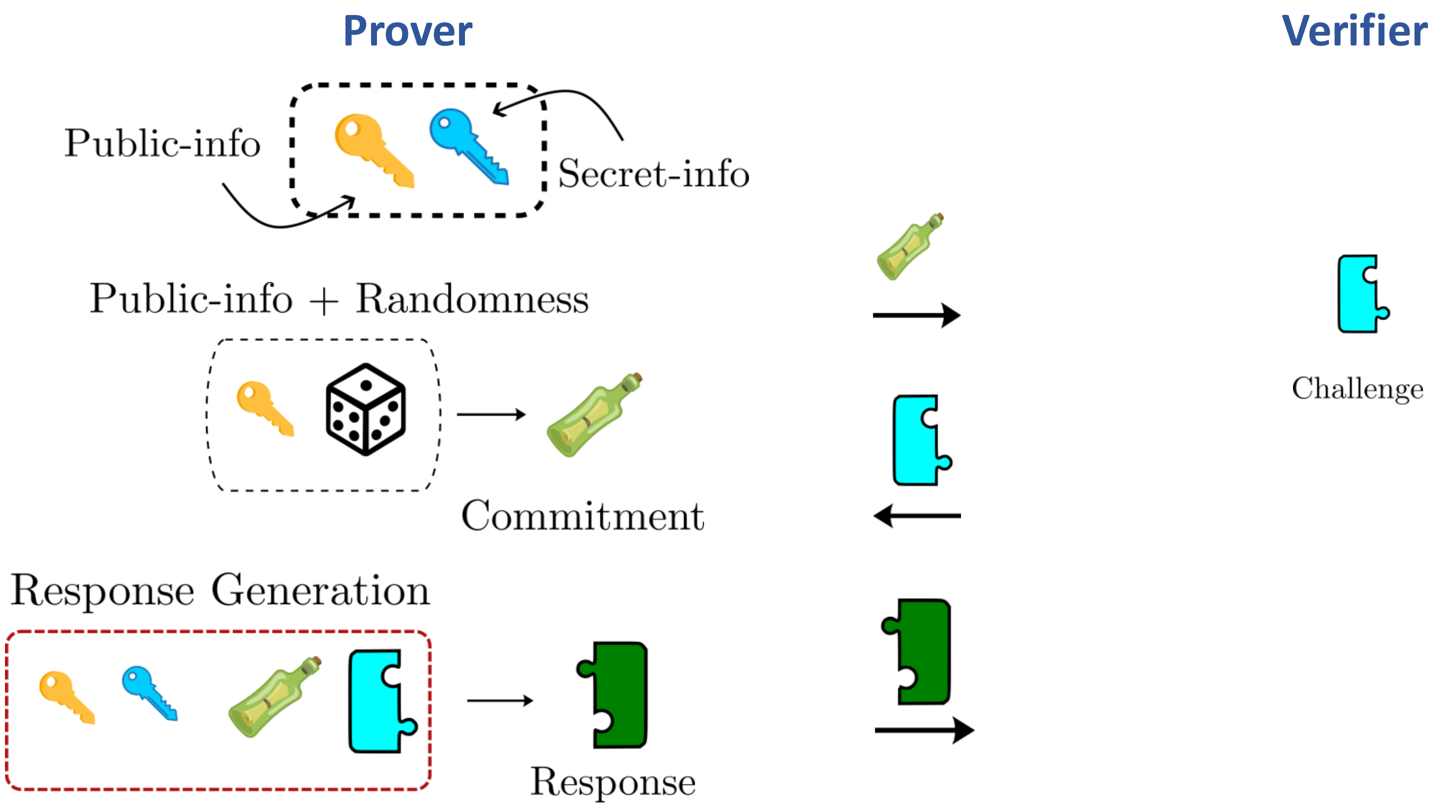

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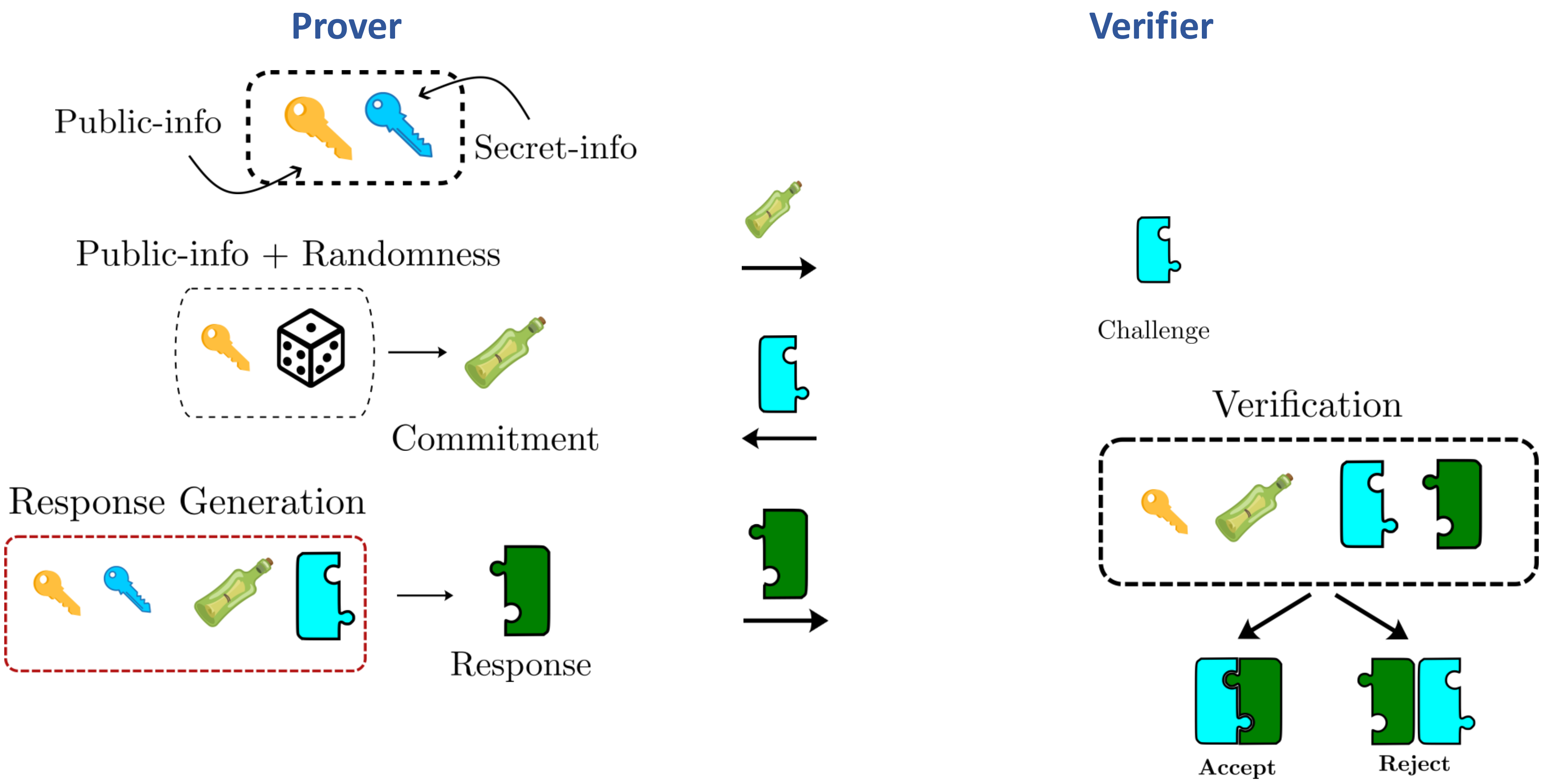

Prover

Verifier

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Commitment

Response Generation

Response

Challenge

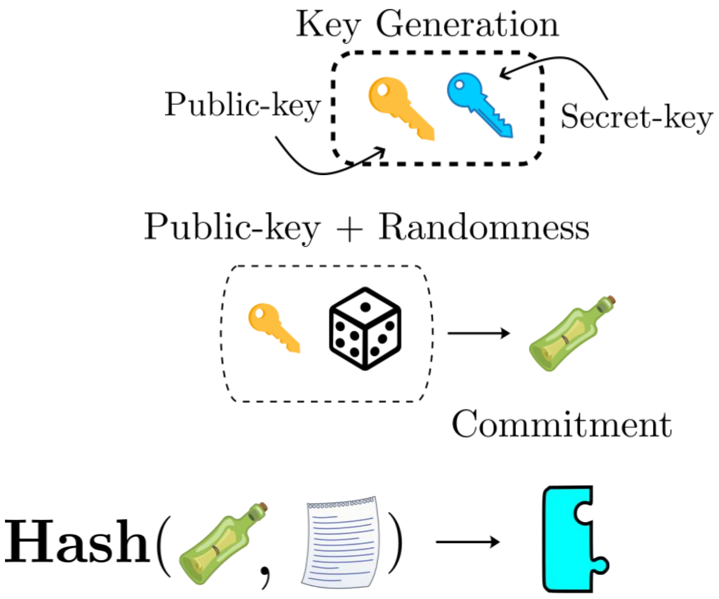
Verification

Accept

Reject

ZK with Fiat-Shamir Transformation

Signer **Verifier**



Key Generation

Public-key

Secret-key

Public-key + Randomness

Commitment

Hash(,) →

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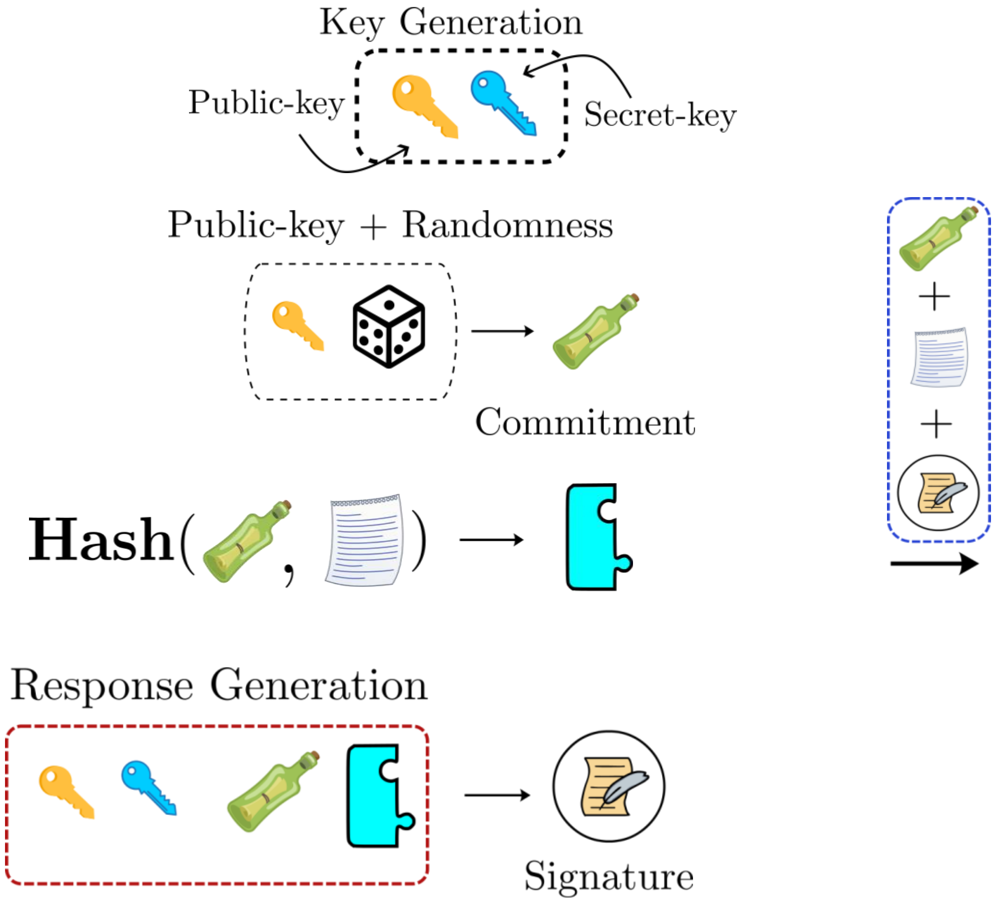

Key Generation

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Public-key + Randomness

Commitment

Hash(,)

Response Generation

Signature

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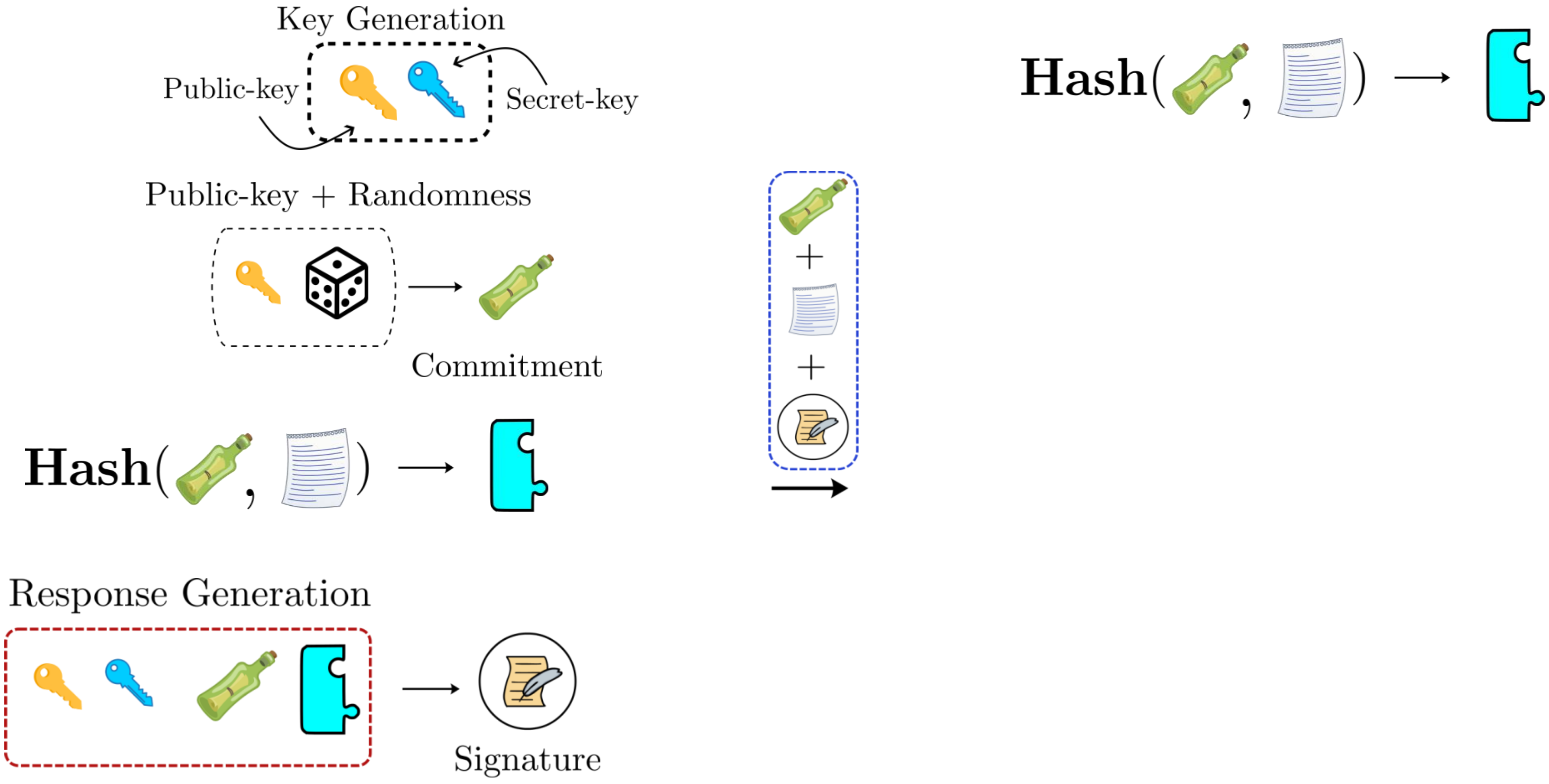

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Commitment

Hash(,) →

+

+

Response Generation

Signature

Hash(,) →

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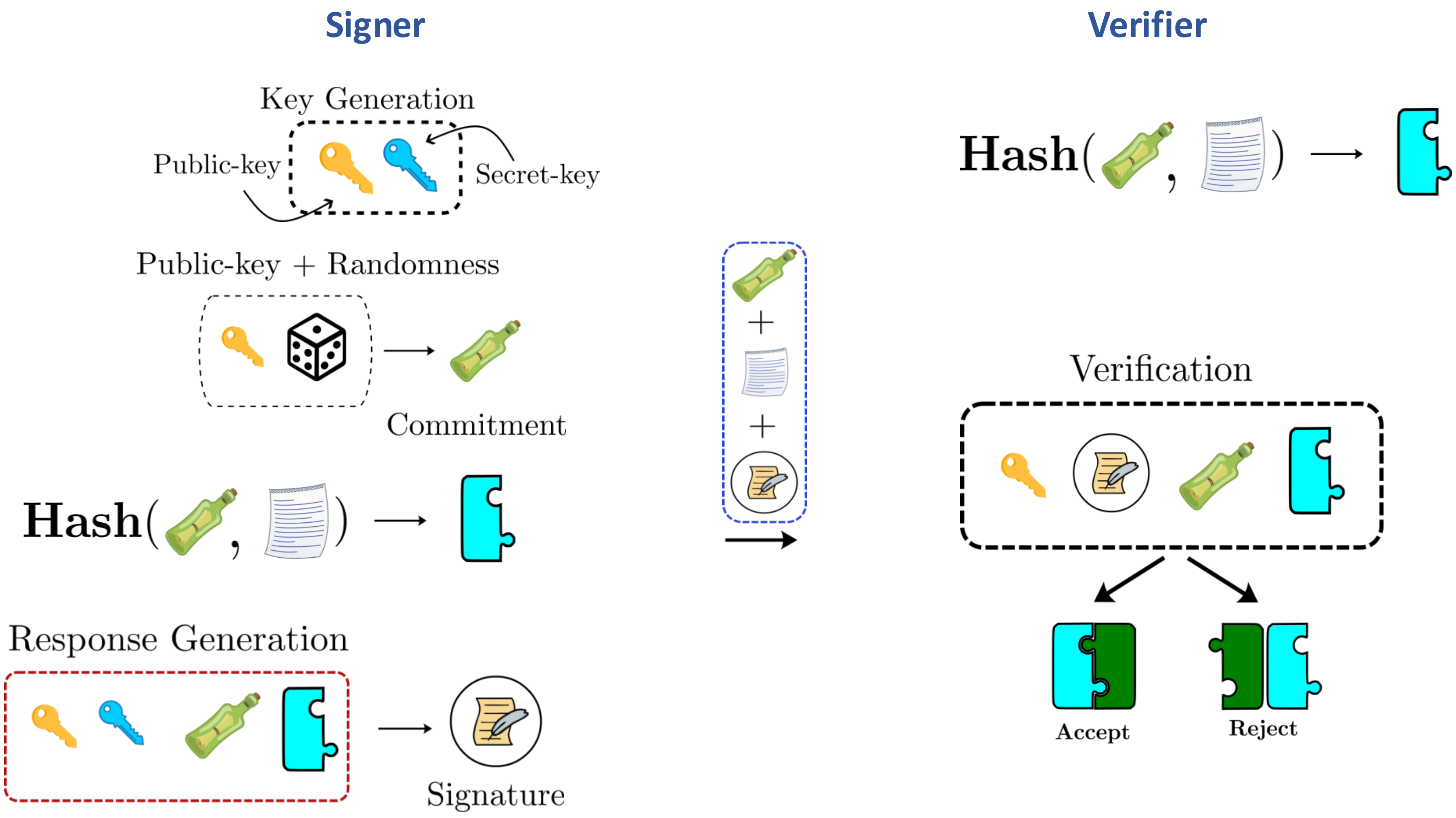

LESS

Signer

Verifier

🔑 : $\boldsymbol{Q}_1, \boldsymbol{Q}_2, \cdots, \boldsymbol{Q}_s$

🔑 : $\boldsymbol{G}_0, \boldsymbol{G}_1 = S(\boldsymbol{G}_0\boldsymbol{Q}_1), \boldsymbol{G}_2, \cdots, \boldsymbol{G}_s$

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Sample : $\boldsymbol{Q}'_1, \boldsymbol{Q}'_2, \cdots, \boldsymbol{Q}'_t$

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$$\boxed{\begin{array}{l} \textbf{Sample}: \boldsymbol{Q}'_1, \boldsymbol{Q}'_2, \cdots, \boldsymbol{Q}'_t \\ \boldsymbol{G}'_1 = S(\boldsymbol{G}_0\boldsymbol{Q}'_1), \boldsymbol{G}'_2, \cdots, \boldsymbol{G}'_t \end{array}}$$

🍾 : $\textbf{Hash}(\boldsymbol{G}'_1, \boldsymbol{G}'_2, \cdots, \boldsymbol{G}'_t)$

Commitment

Challenge

$\textbf{Hash}($ 🍾, 📄 $) \longrightarrow$ 🧩 : $\mathbf{c_1}, \mathbf{c_2}, \cdots, \mathbf{c_t} \in \{\mathbf{0}, \cdots, \mathbf{s}\}$

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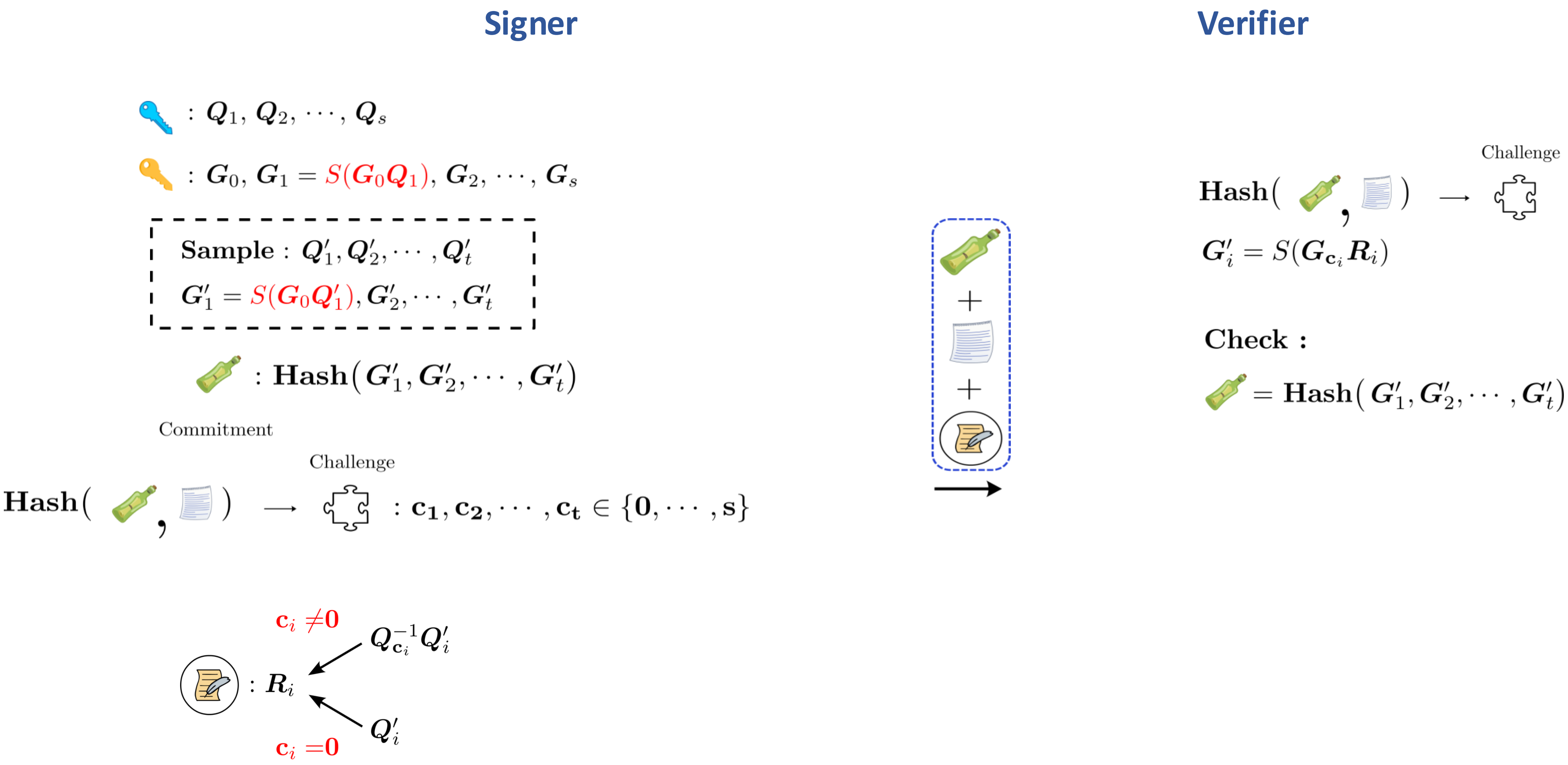
$$\begin{tikzcd} & \boldsymbol{Q}_{\mathbf{c}_i}^{-1}\boldsymbol{Q}'_i \arrow[dl, "\mathbf{c}_i \neq \mathbf{0}"'] \\ ✍ : \boldsymbol{R}_i & \\ & \boldsymbol{Q}'_i \arrow[ul, "\mathbf{c}_i = \mathbf{0}"] \end{tikzcd}$$

LESS



Signer

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Commitment

Challenge

$\mathbf{Hash}($ 🍾, 📄 $) \longrightarrow$ 🧩 : $\mathbf{c_1}, \mathbf{c_2}, \cdots, \mathbf{c_t} \in \{\mathbf{0}, \cdots, \mathbf{s}\}$

$\mathbf{c}_i \neq \mathbf{0}$: $\boldsymbol{Q}_{\mathbf{c}_i}^{-1}\boldsymbol{Q}'_i$

✍ : $\boldsymbol{R}_i$

$\mathbf{c}_i = \mathbf{0}$: $\boldsymbol{Q}'_i$

🍾 + 📄 + ✍ →

Verifier

Challenge

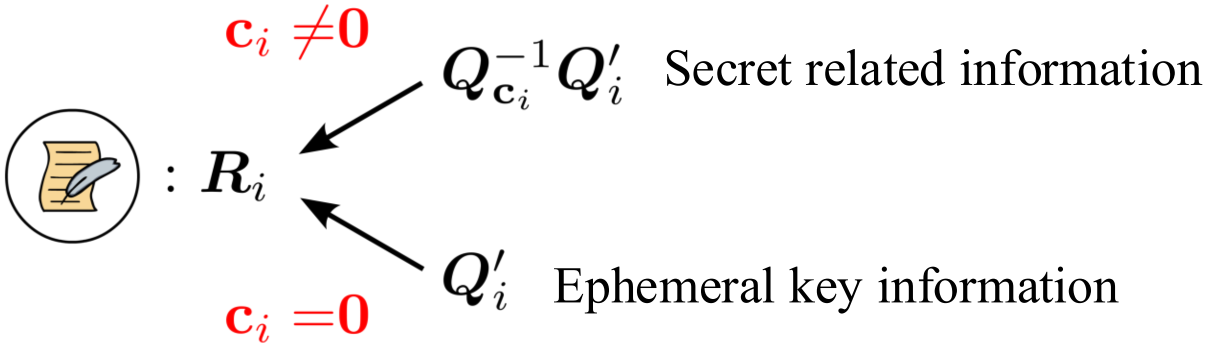
$\mathbf{Hash}($ 🍾, 📄 $) \longrightarrow$ 🧩

$\boldsymbol{G}'_i = S(\boldsymbol{G}_{\mathbf{c}_i}\boldsymbol{R}_i)$

Check :

🍾 $= \mathbf{Hash}(\boldsymbol{G}'_1, \boldsymbol{G}'_2, \cdots, \boldsymbol{G}'_t)$

Target of Our Fault Attack



$\mathbf{c}_i \neq \mathbf{0}$

$\boldsymbol{Q}_{\mathbf{c}_i}^{-1}\boldsymbol{Q}'_i$ Secret related information

: $\boldsymbol{R}_i$

$\boldsymbol{Q}'_i$ Ephemeral key information

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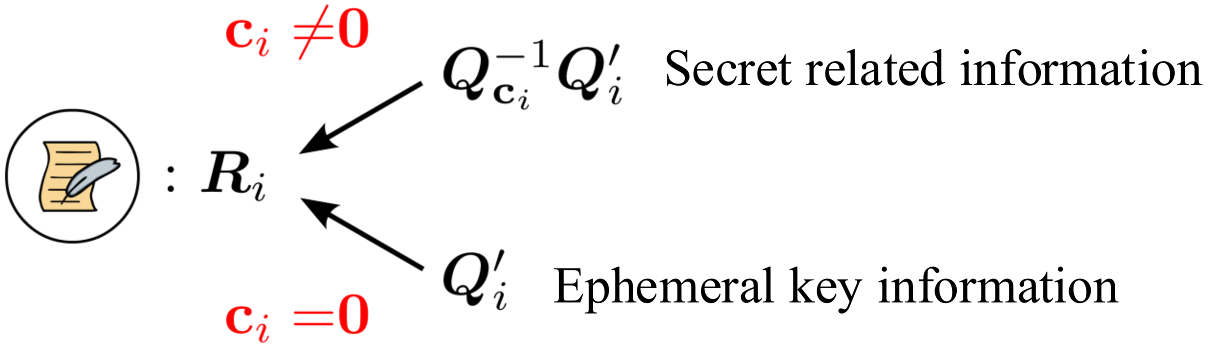

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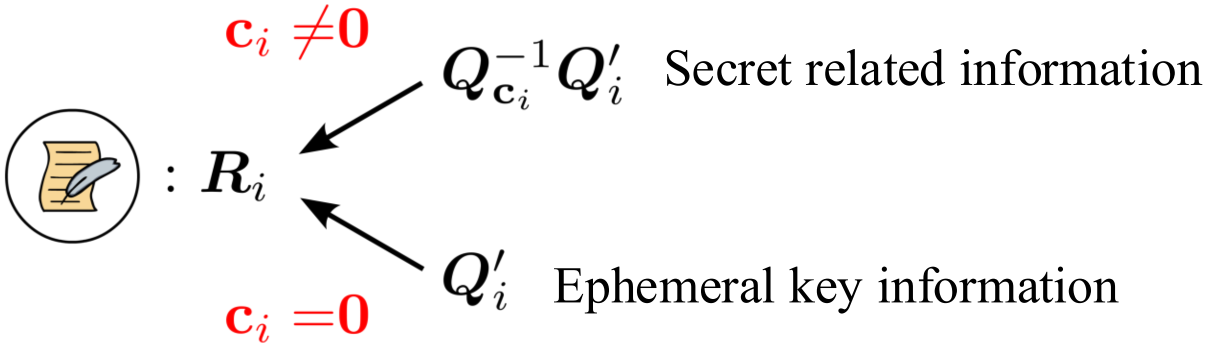

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- If we have both $\mathbf{Q'}_i$ and $\mathbf{Q}^{-1}{}_{\mathbf{ci}}\mathbf{Q'}_i$, then the secret $\mathbf{Q}_{\mathbf{ci}}\mathbf{=Q'}_i\mathbf{(Q}^{-1}{}_{\mathbf{ci}}\mathbf{Q'}_i\mathbf{)}^{-1}$ will be recovered.

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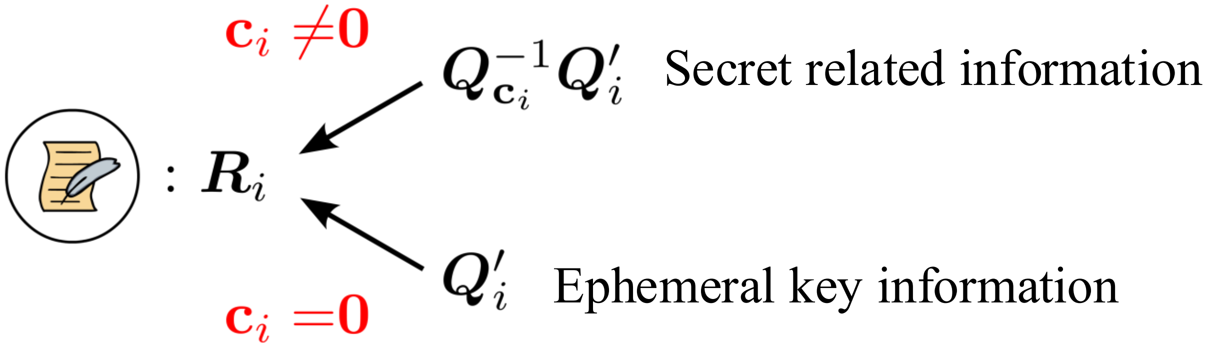

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Target

Get a pair $(\mathbf{Q'}_i,\mathbf{Q}^{-1}_{ci}\mathbf{Q'}_i)$

Fault Assumption and Result

- Our fault assumption is we can change the value of a location from 1 to 0

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- This can be achieved by any one of
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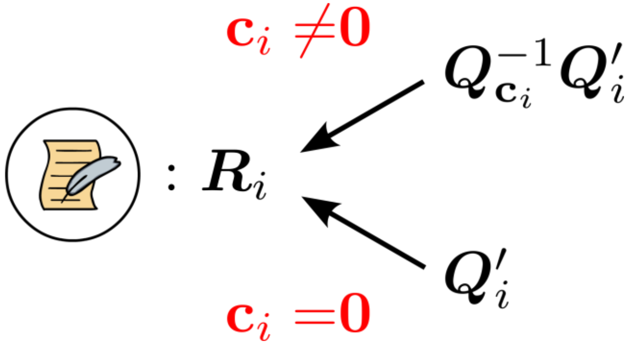
Scheme name	Security level	Parameter set	Required faults for complete secret recovery
LESS	1	Less-1b	**1**
		Less-1i	**1**
		Less-1s	**2**
	3	Less-3b	**1**
		Less-3s	**1**
	5	Less-5b	**1**
		Less-5s	**1**
CROSS	1, 3, 5	CROSS-R-SDP	**1**
		CROSS-R-SDPG	**1**

Overview of LESS



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$\boldsymbol{Q}_{\mathbf{c}_i}^{-1}\boldsymbol{Q}'_i$

$: \boldsymbol{R}_i$

$\boldsymbol{Q}'_i$

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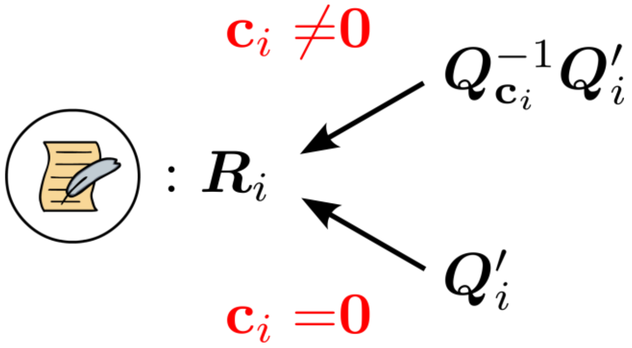
Overview of LESS

- Each **Q'**$_i$ is generated from a random seed **seed**$_i$



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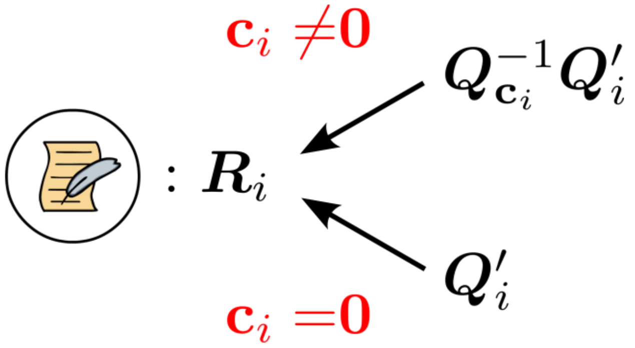
Overview of LESS

- Each **Q'$_i$** is generated from a random seed **seed$_i$**
- The challenge **c=c$_1$,c$_2$,..,c$_t$** is of fixed weight w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Overview of LESS

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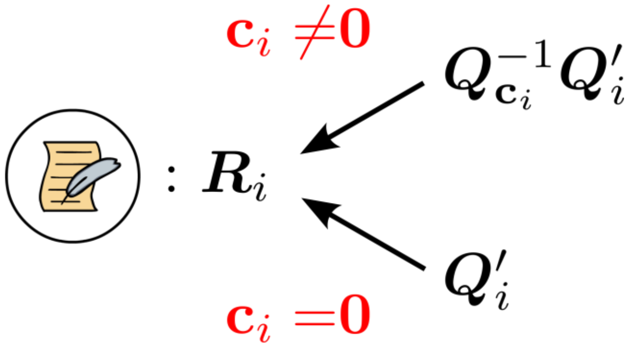
- The response must contain information of (t-w) many seeds of $\mathbf{Q'}_\mathbf{i}$


$\mathbf{c}_i \neq \mathbf{0}$
$Q_{\mathbf{c}_i}^{-1} Q'_i$
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Q'_i
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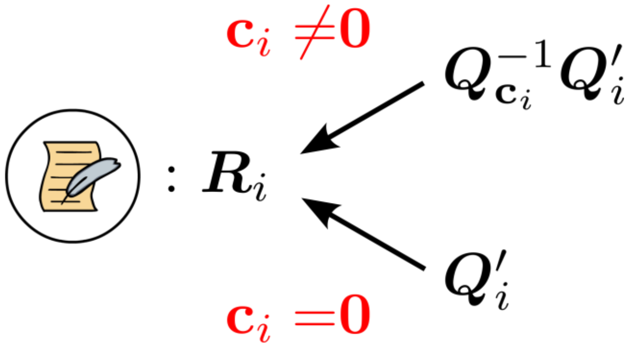
- For parameter, LESS-5b signature size 74960 Bytes



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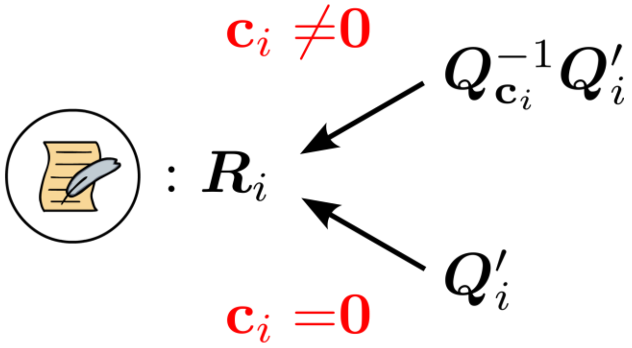

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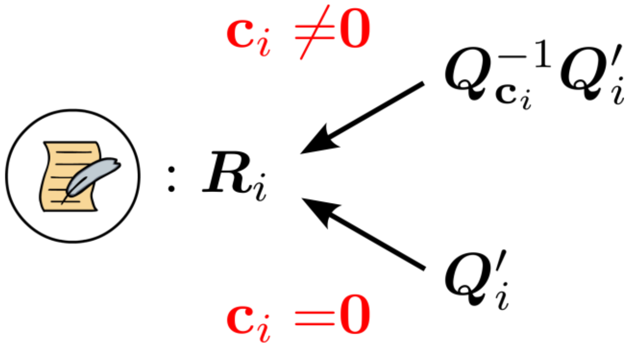
- Compressed signatures size: ~32500 Bytes (~57% reduced)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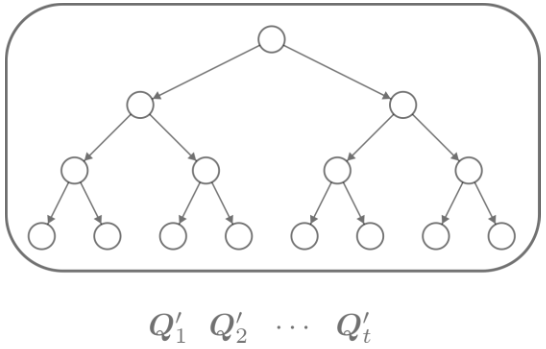
Summary of Signature Compression

Step 1

Generate a GGM tree (seedtree) and generate all the ephimeral keys Q_1', Q_2', … ,Q_t'



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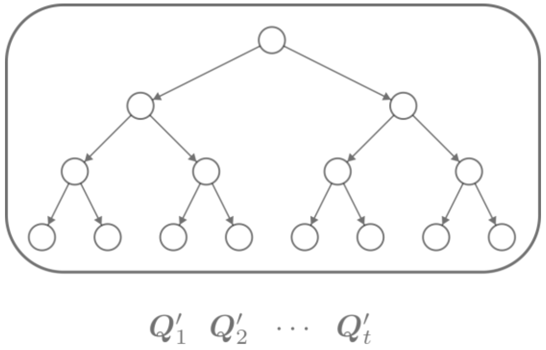
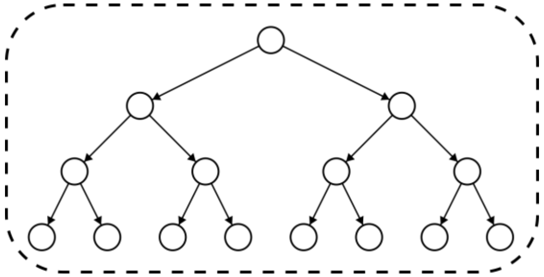


Step 2

Generate a reference tree based on the challenge



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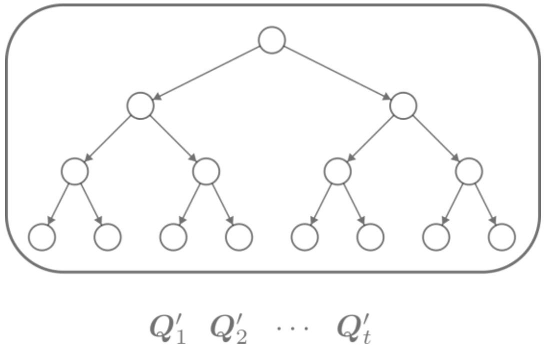

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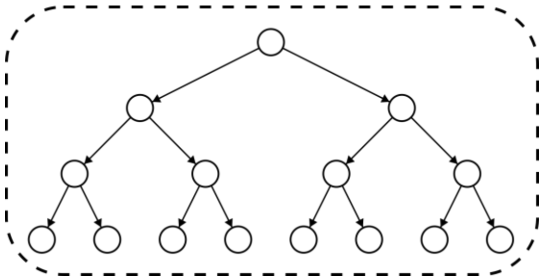

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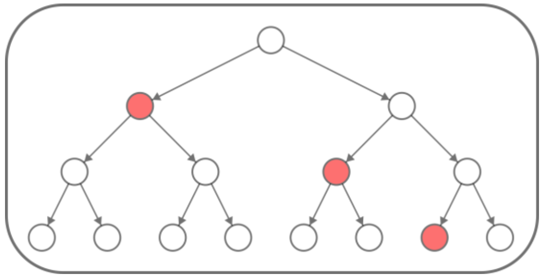

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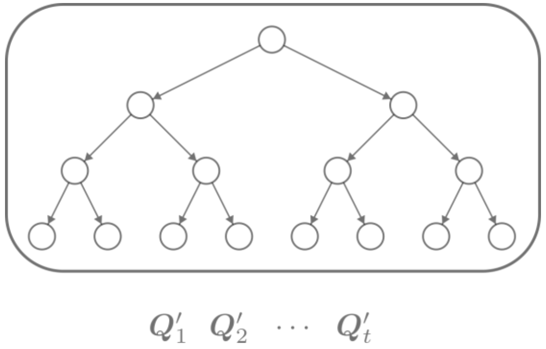

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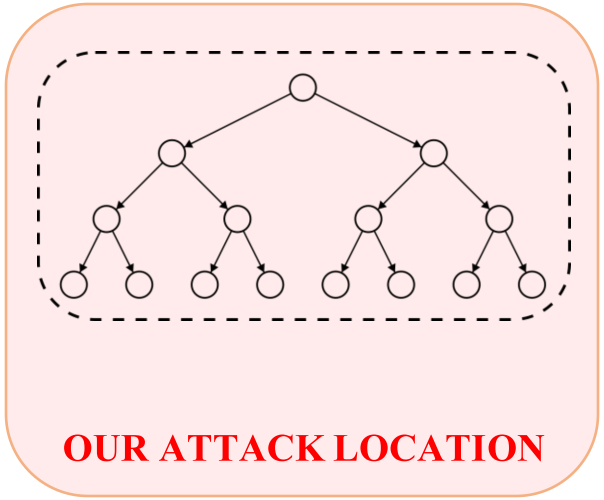

OUR ATTACK LOCATION

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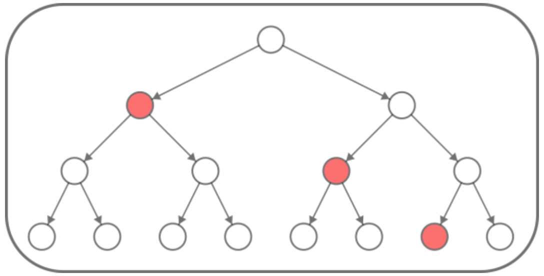
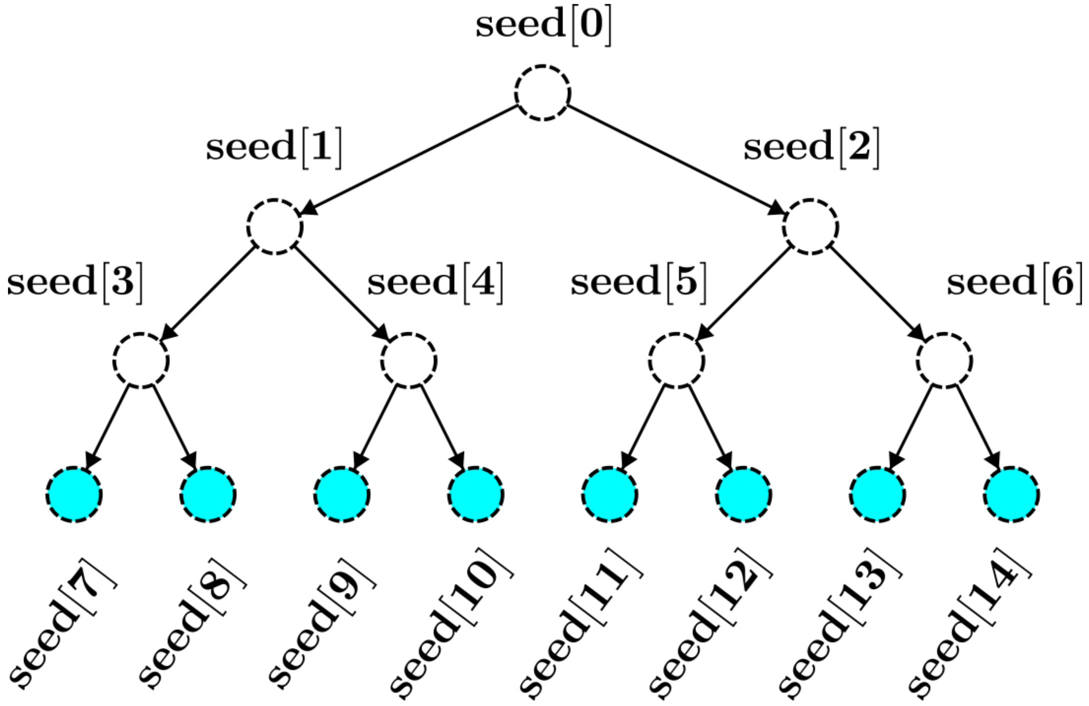


Seed Tree Generation



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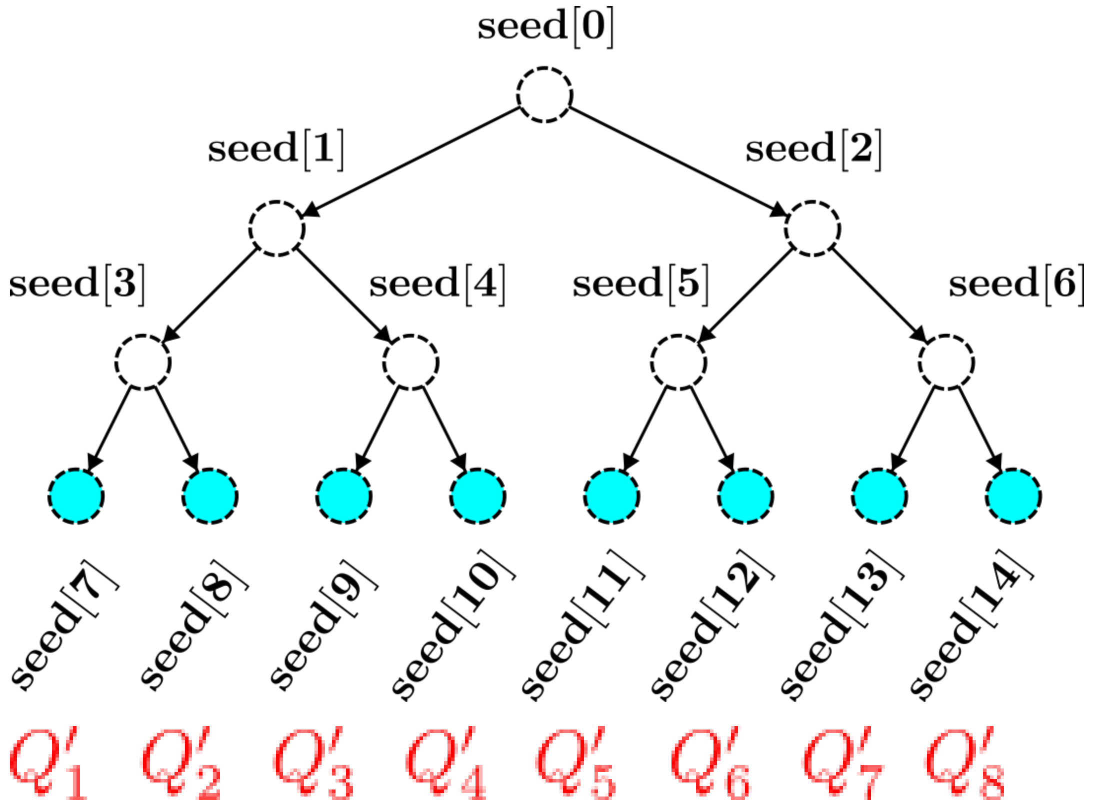
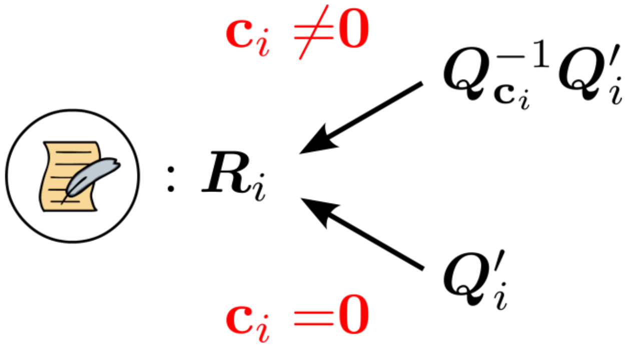


Compression Technique



$\mathbf{c}_i \neq \mathbf{0}$

$\boldsymbol{Q}_{\mathbf{c}_i}^{-1}\boldsymbol{Q}'_i$

$: \boldsymbol{R}_i$

$\boldsymbol{Q}'_i$

$\mathbf{c}_i = \mathbf{0}$

Suppose **c=(0,0,0,0,1,0,0,2)**

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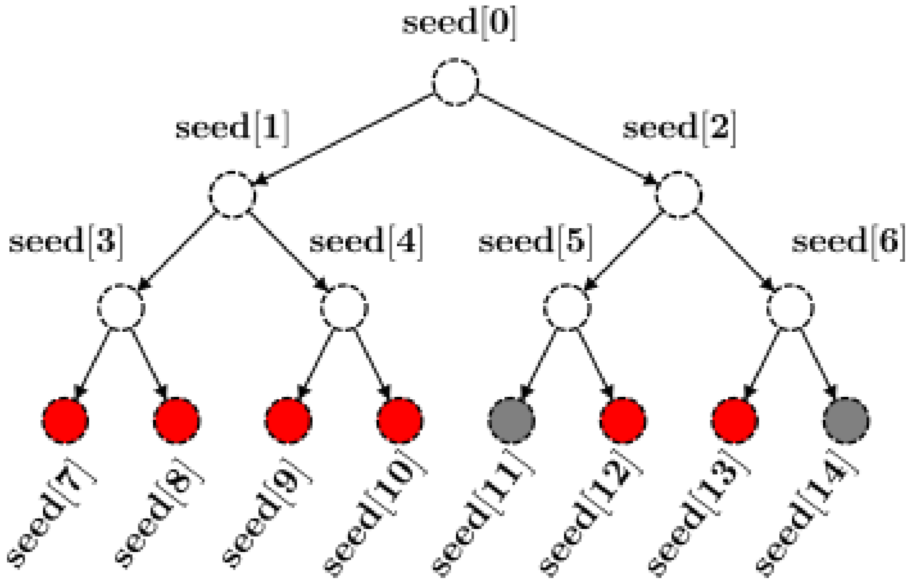

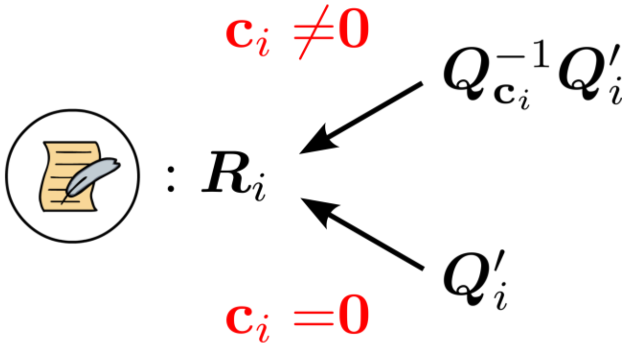

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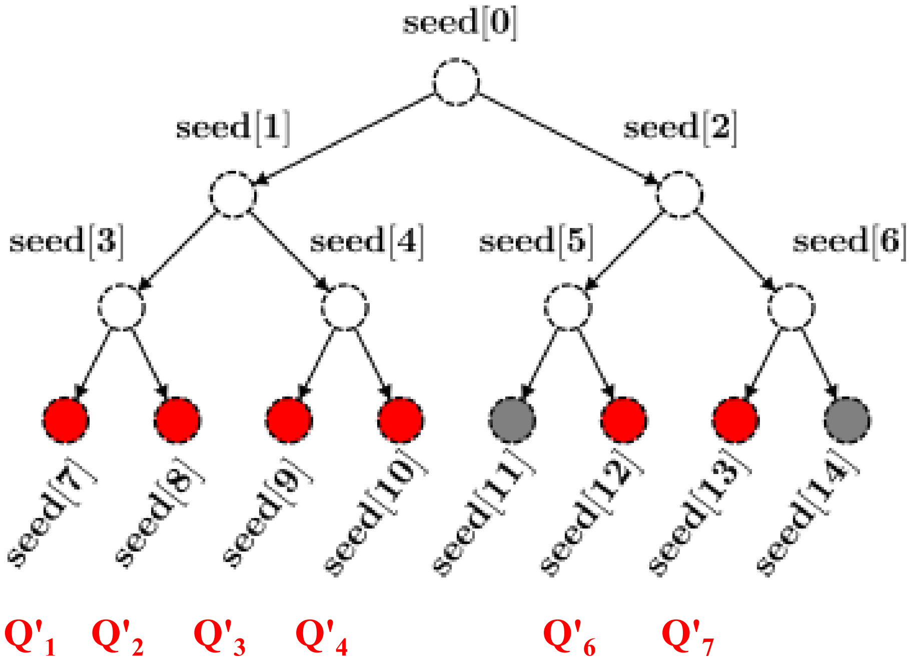

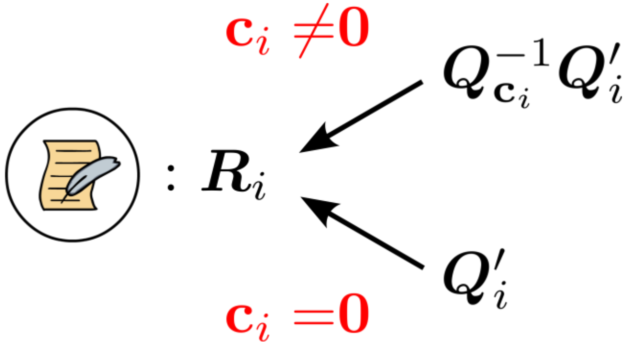
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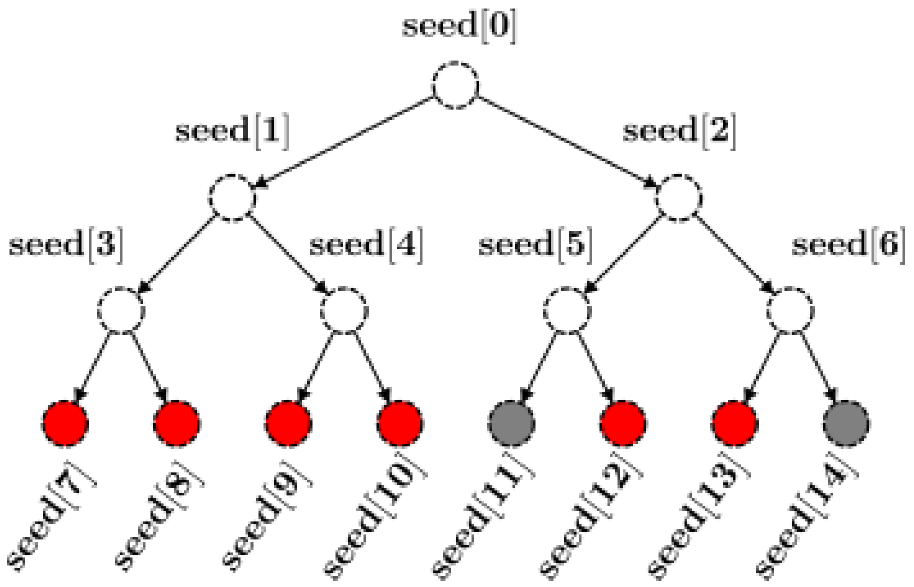
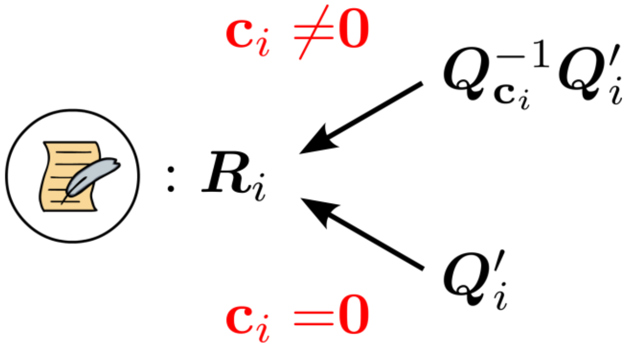


Q'_1 Q'_2 Q'_3 Q'_4 $Q^{-1}_1Q'_5$ Q'_6 Q'_7 $Q^{-1}_2Q'_8$



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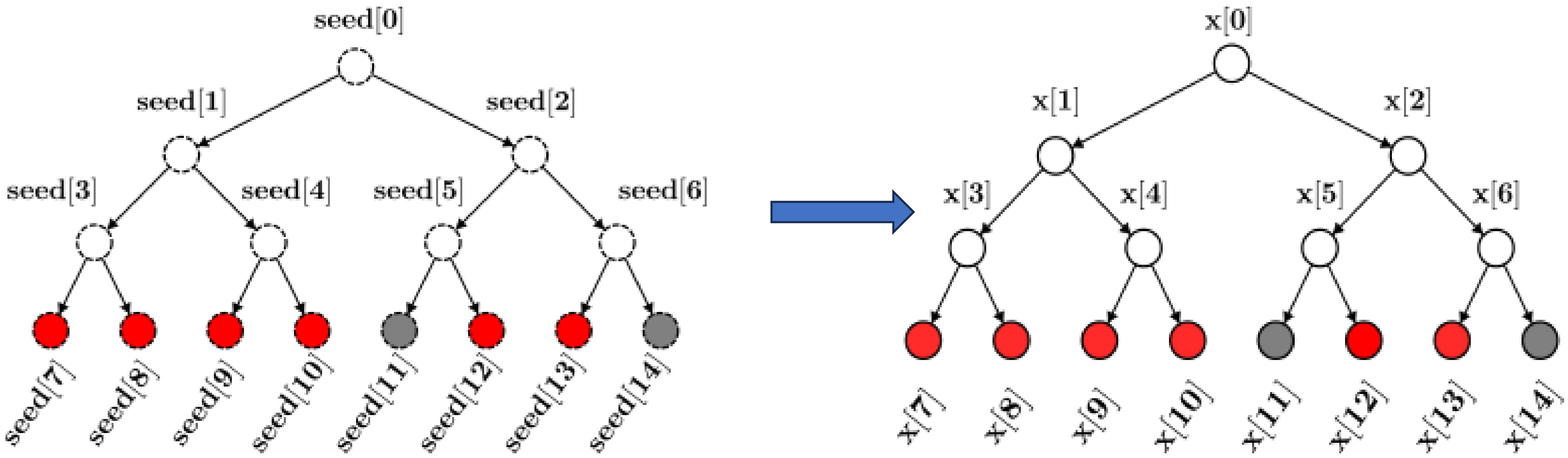

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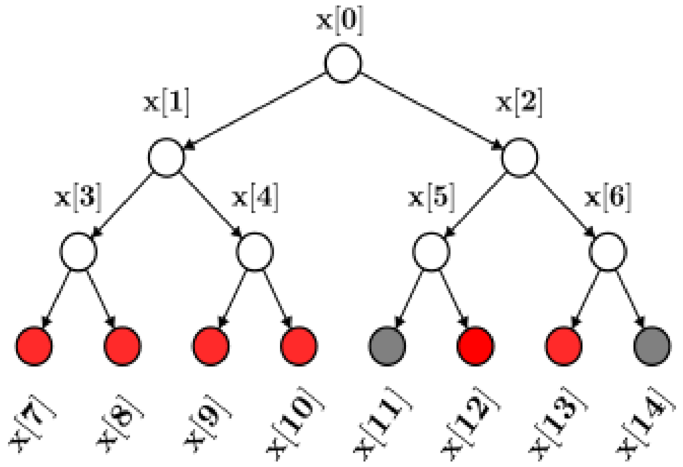

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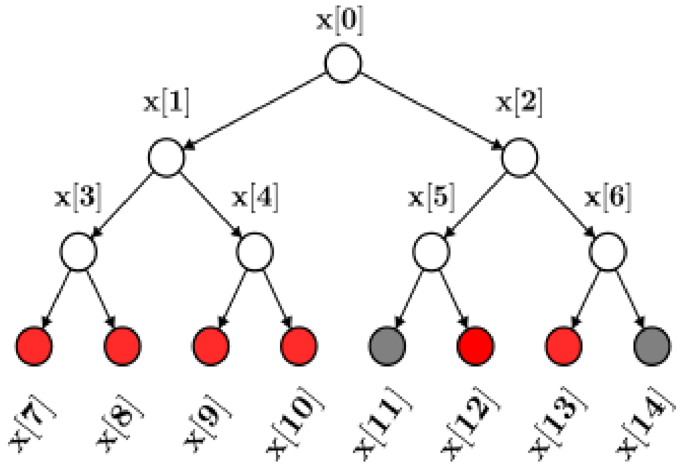

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i-th node: 🔴 if both children are 🔴

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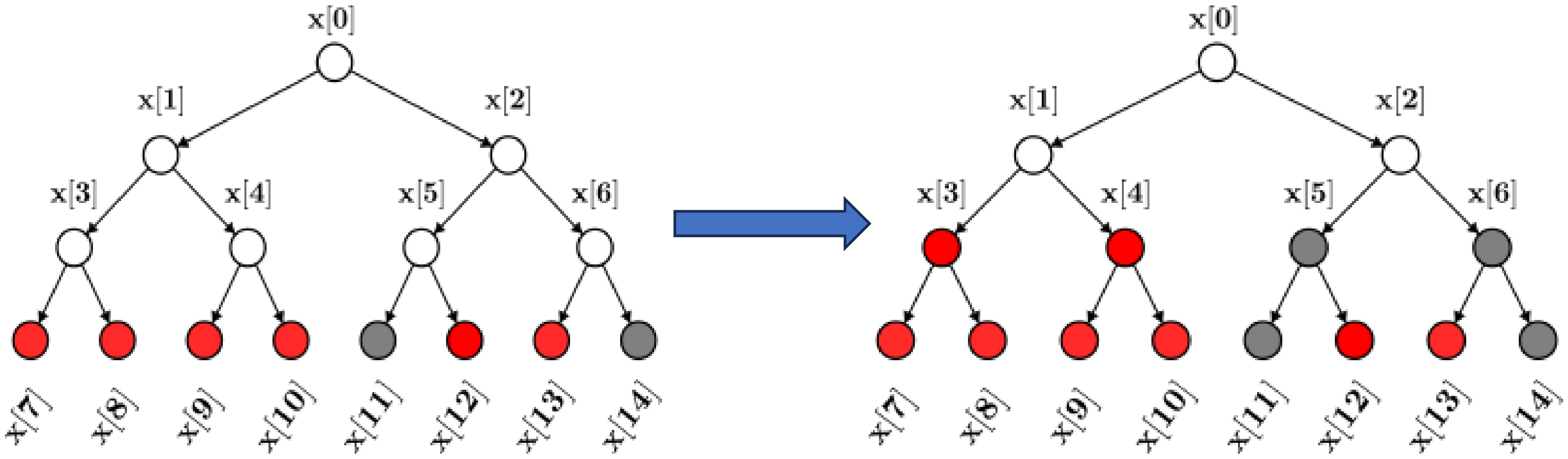

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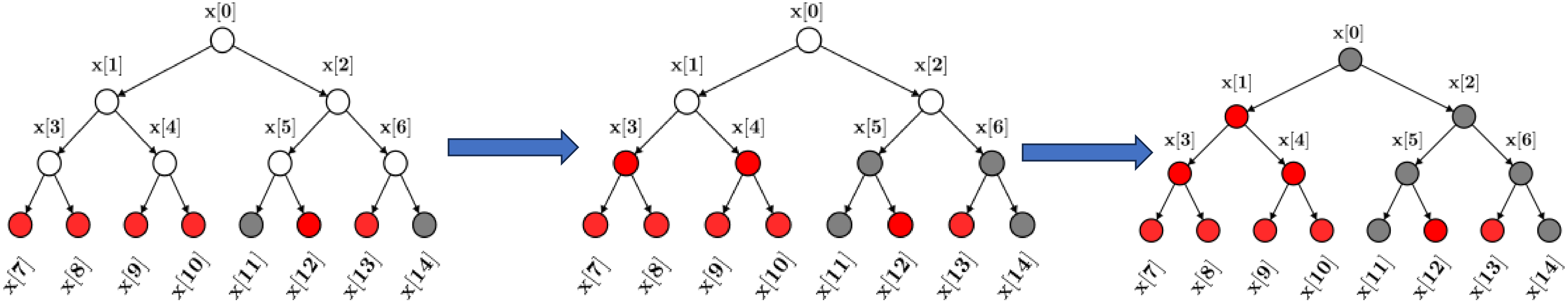

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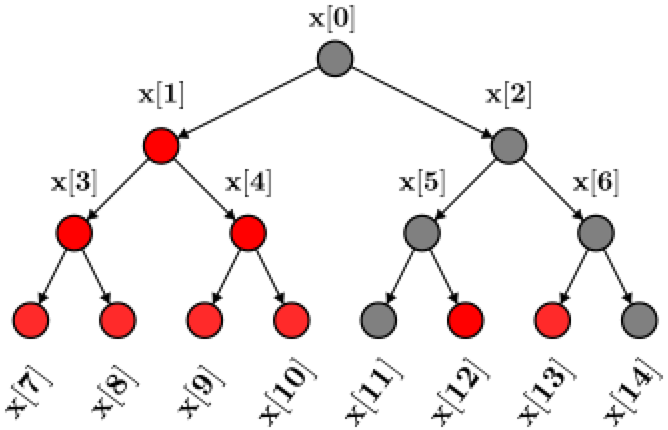

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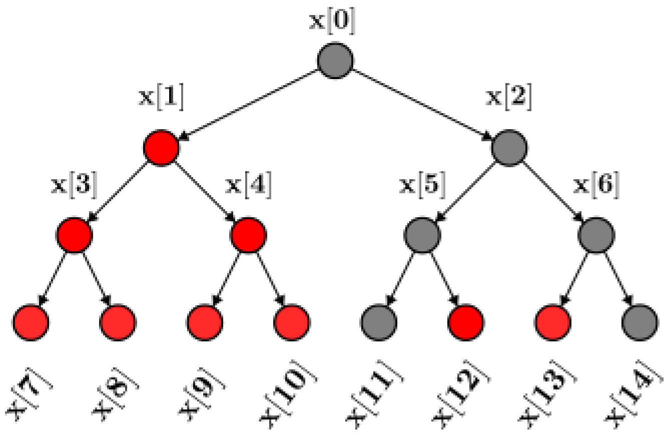

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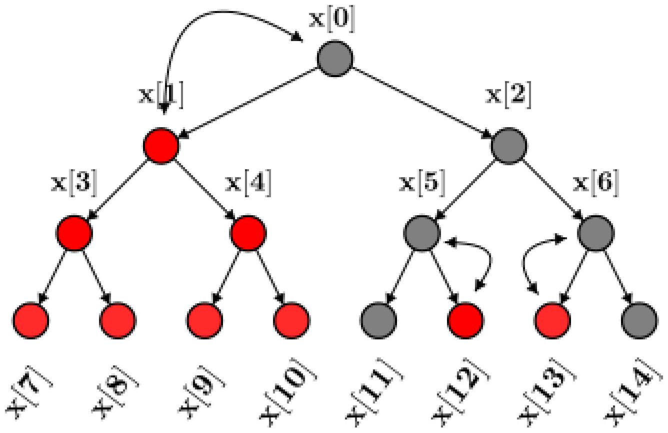

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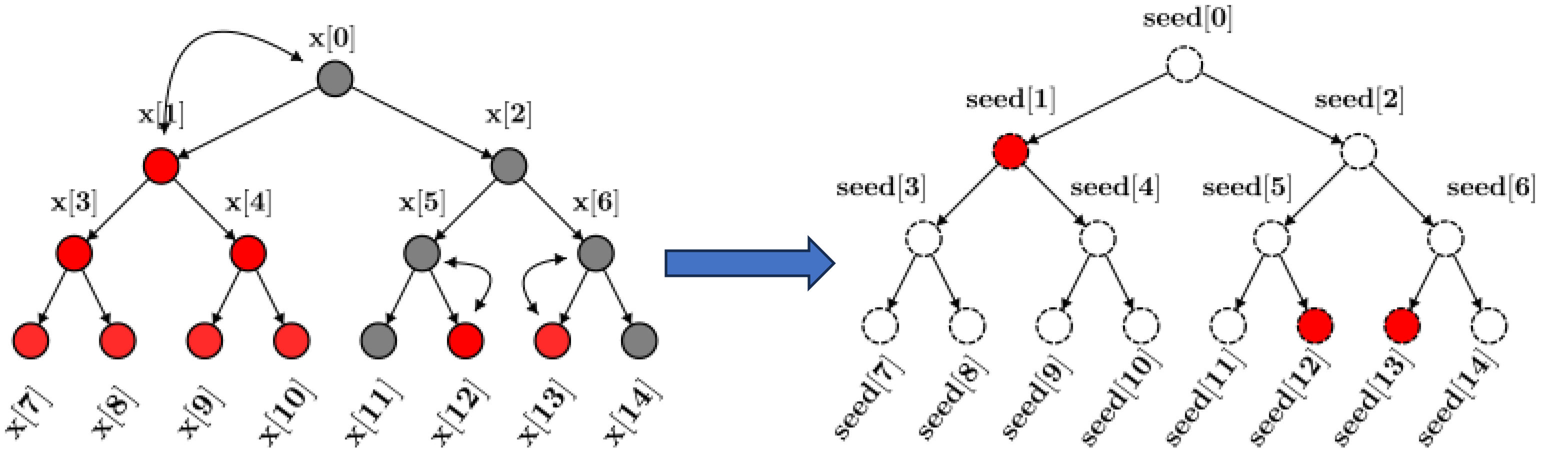

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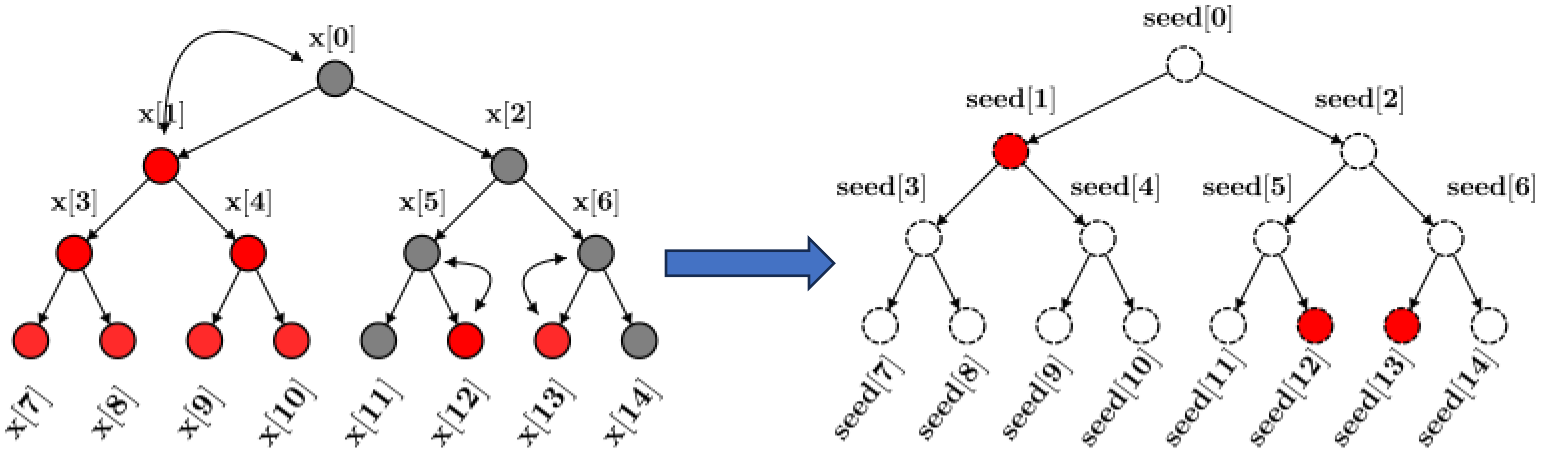

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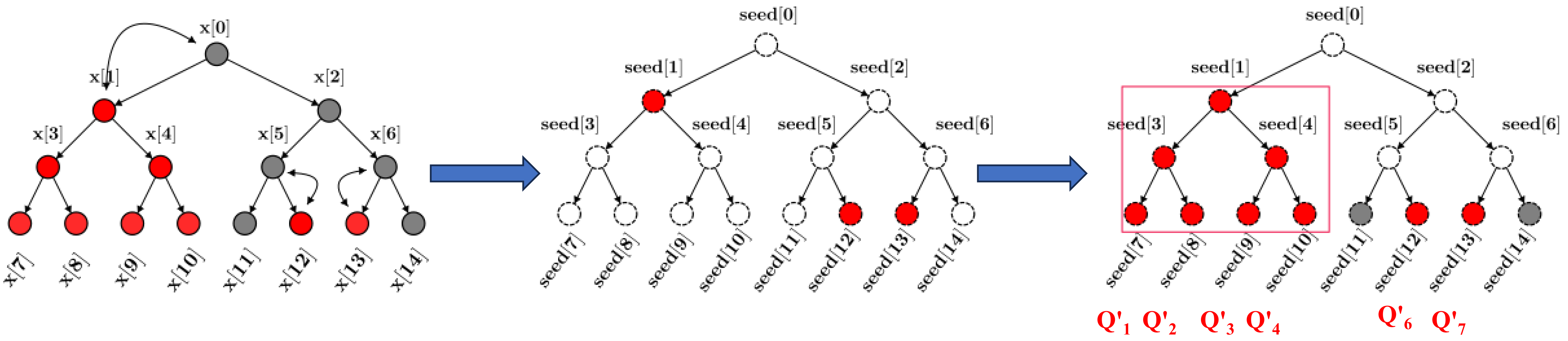

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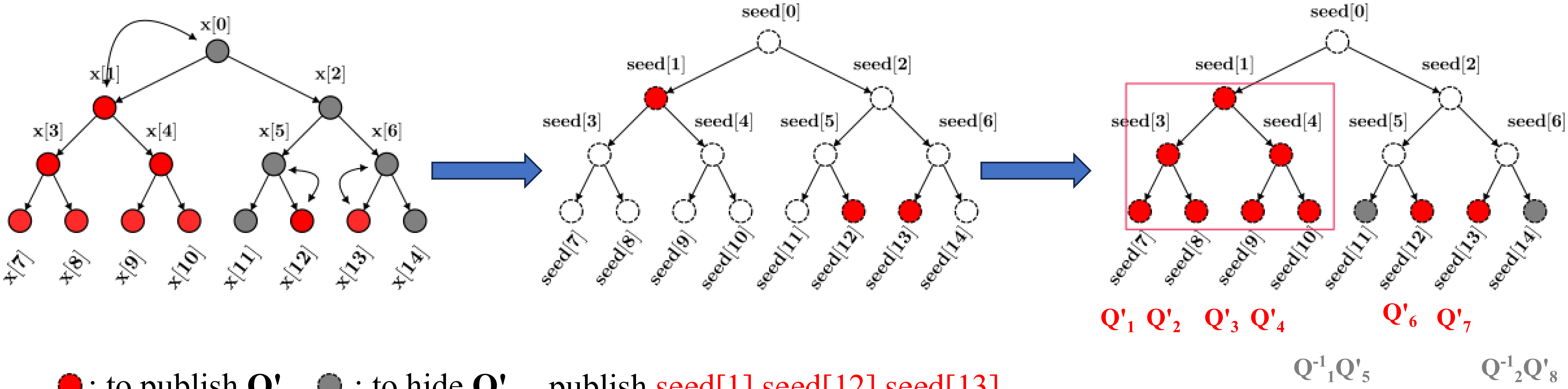

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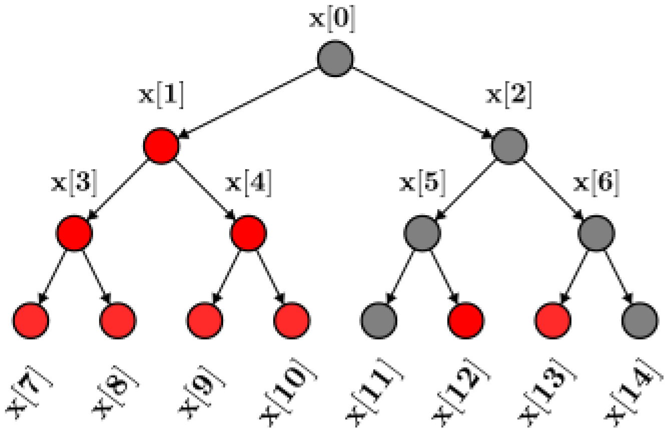

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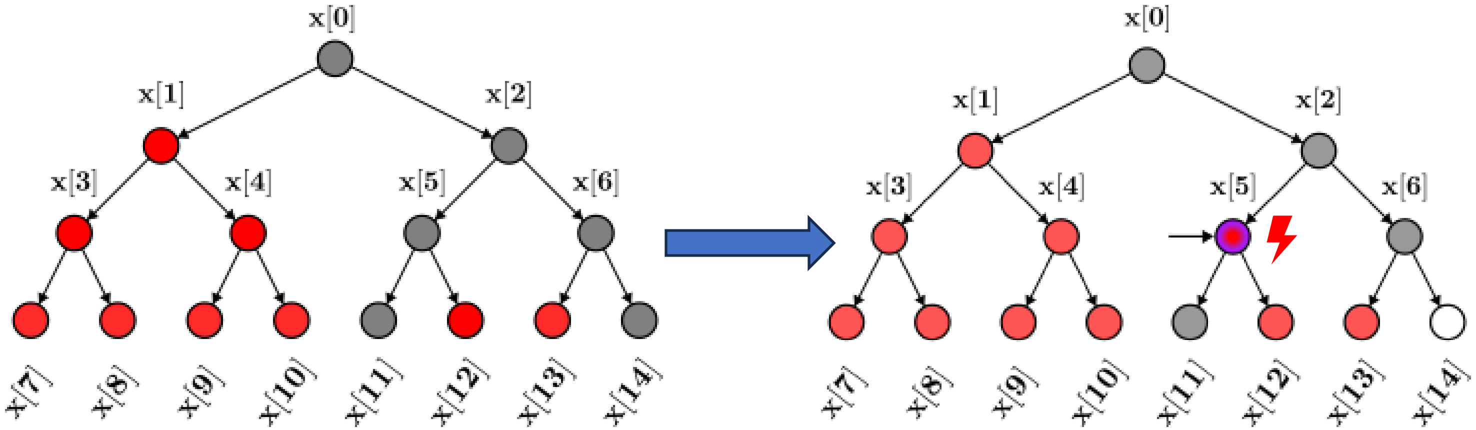

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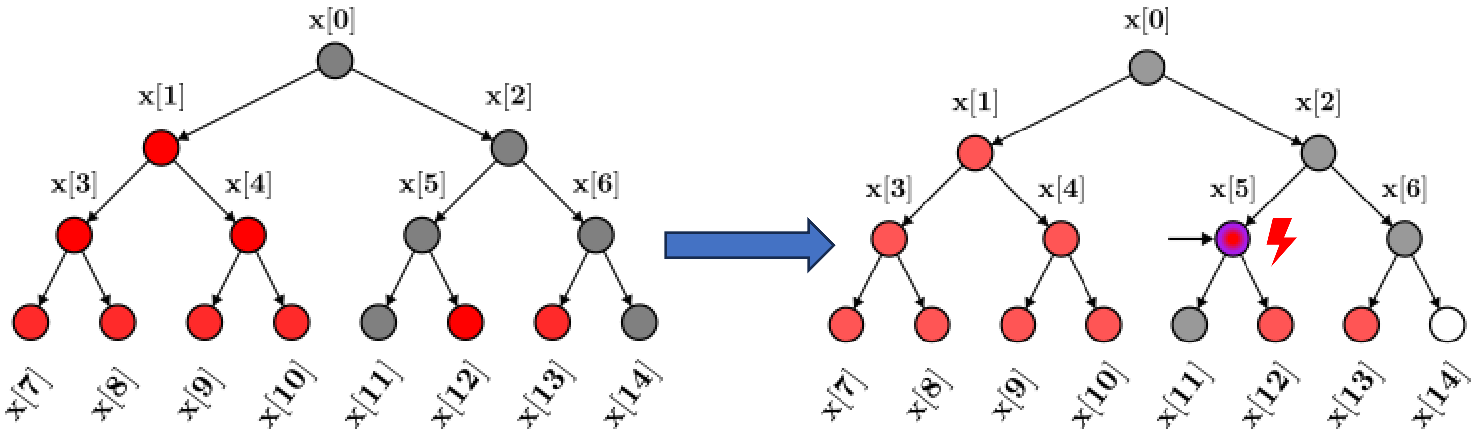

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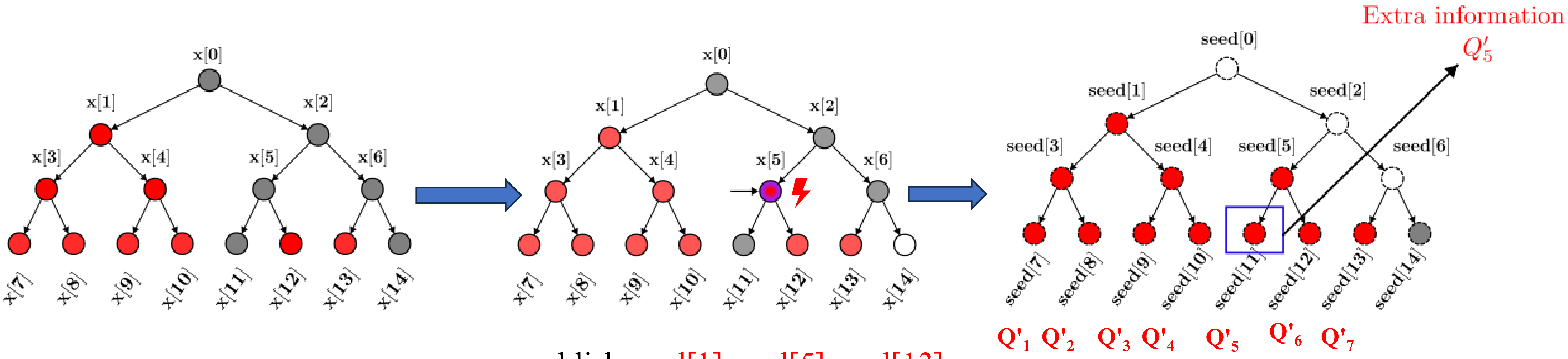

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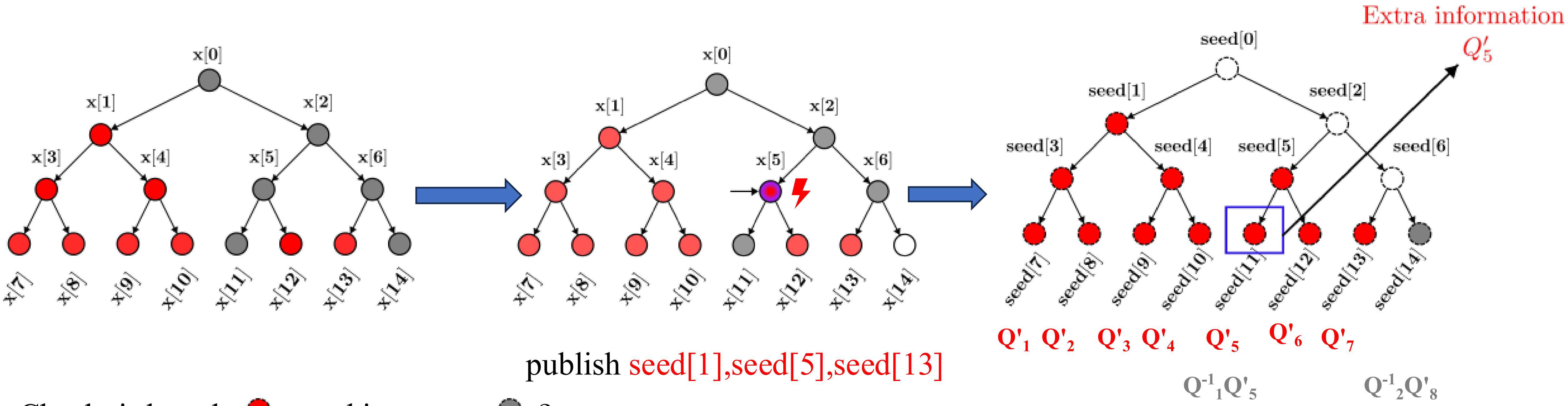

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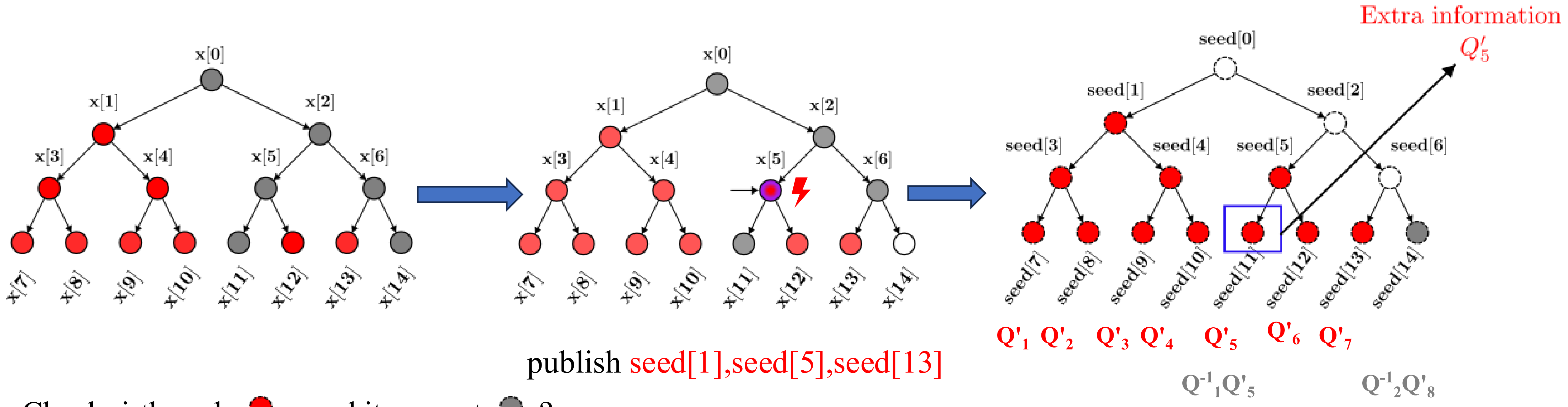

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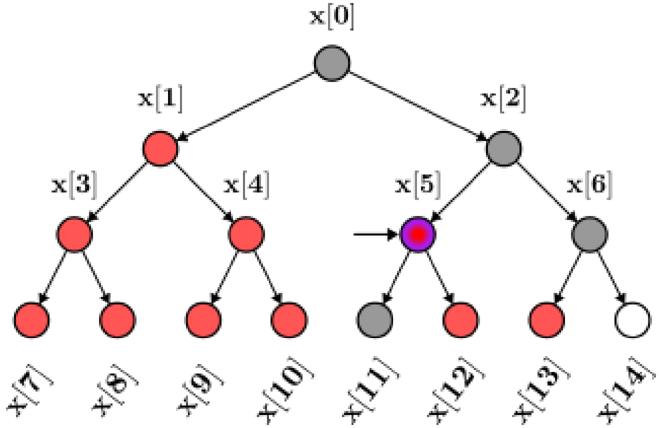
The secret Q_1 can be computed by

$$Q_1 = Q'_5 (Q^{-1}_1 Q'_5)^{-1}$$

Leaks secret information!!!!

Generic Fault Location



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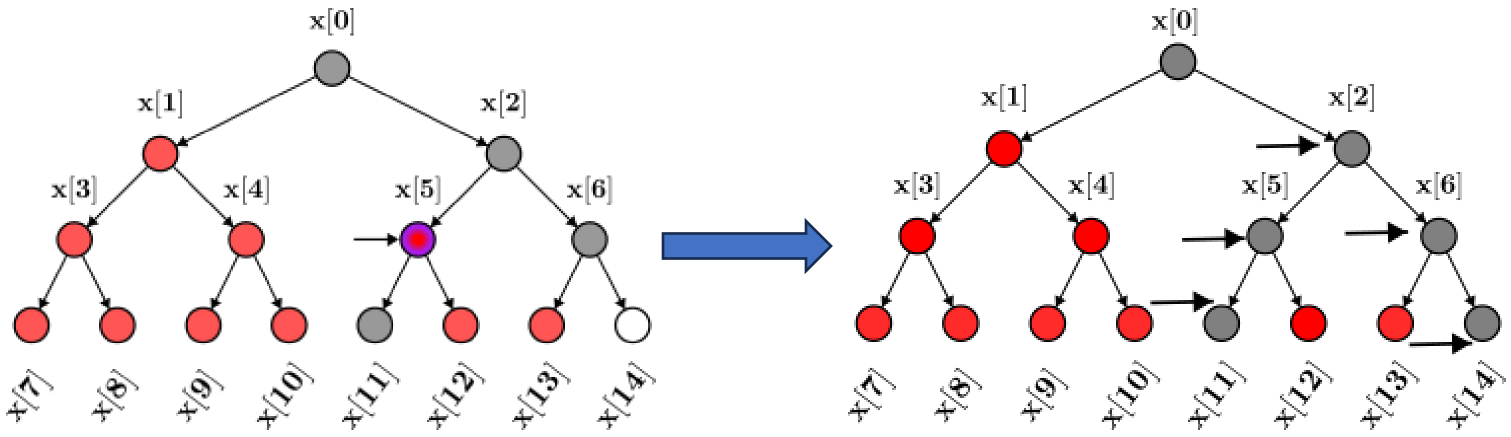

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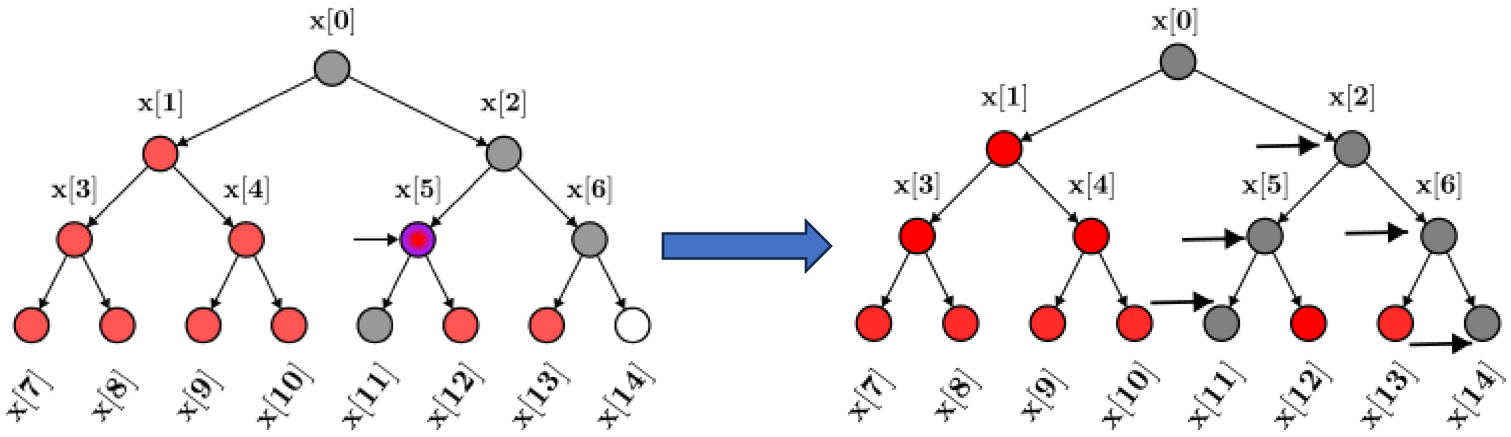

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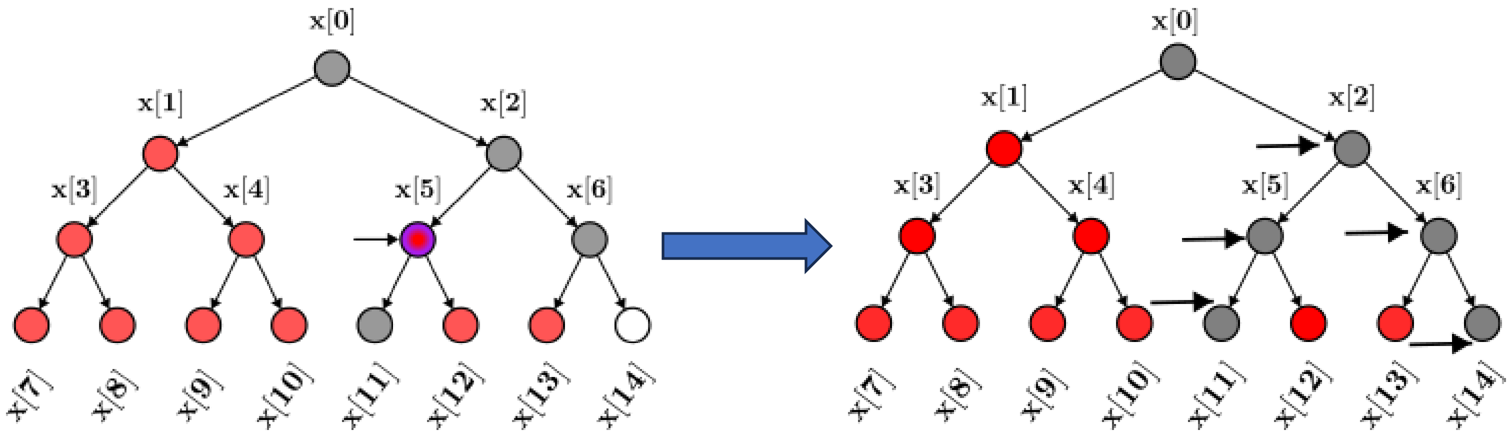

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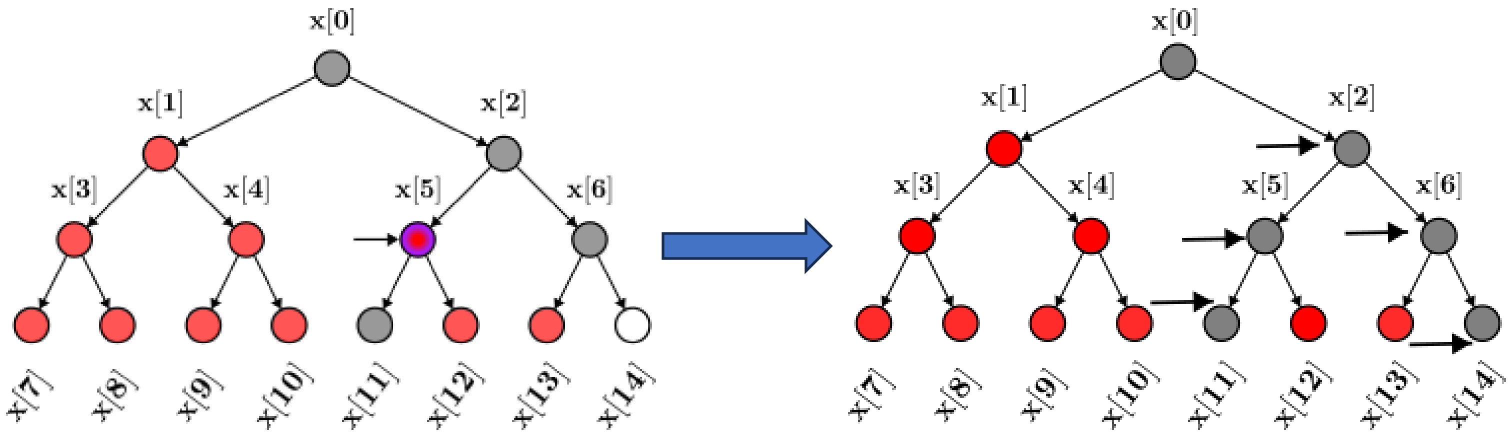

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- For our result, we have targeted the location x[1]/x[2]

Fault Detection

- After Fault injection we need to answer the questions:
  - Is the fault injected exactly at i-th location?
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- In our work, the fault detection method answers both of the above questions.

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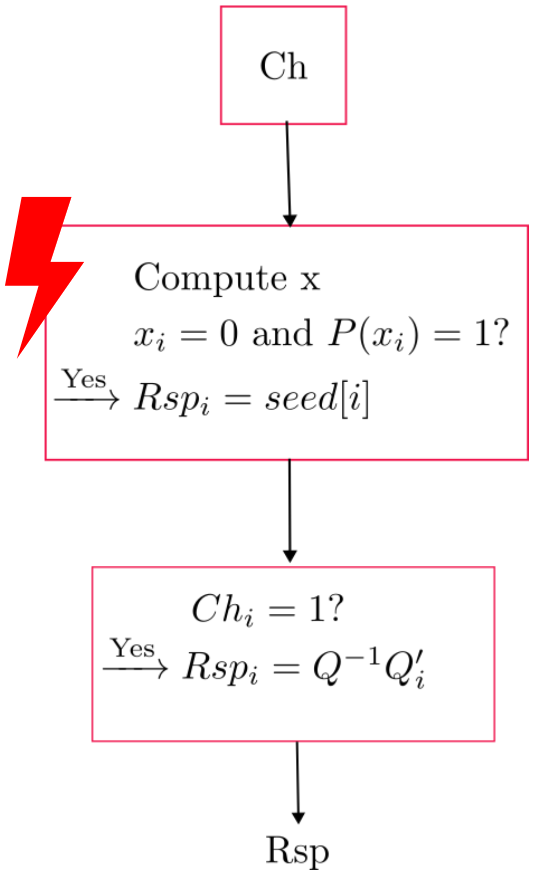
Ch
Compute x
$x_i = 0$ and $P(x_i) = 1$?
$\xrightarrow{\text{Yes}} Rsp_i = seed[i]$
$Ch_i = 1$?
$\xrightarrow{\text{Yes}} Rsp_i = Q^{-1}Q'_i$
Rsp

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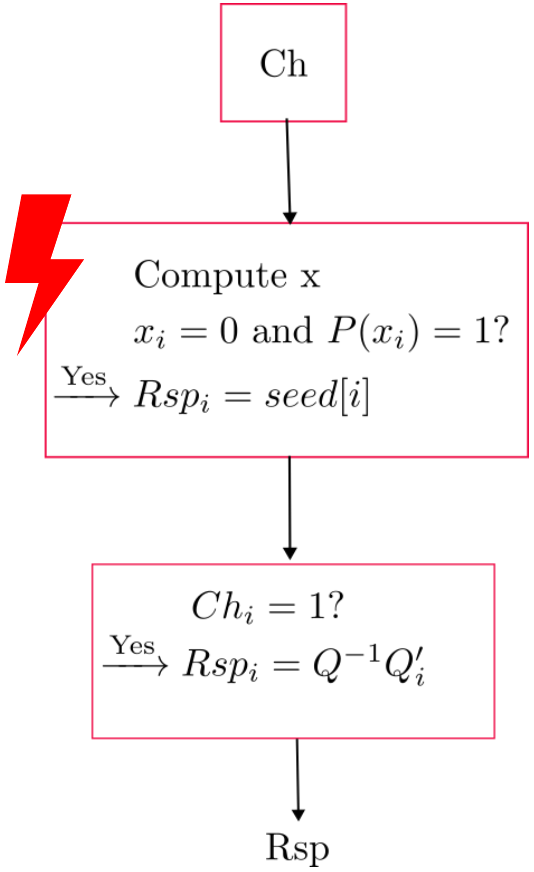

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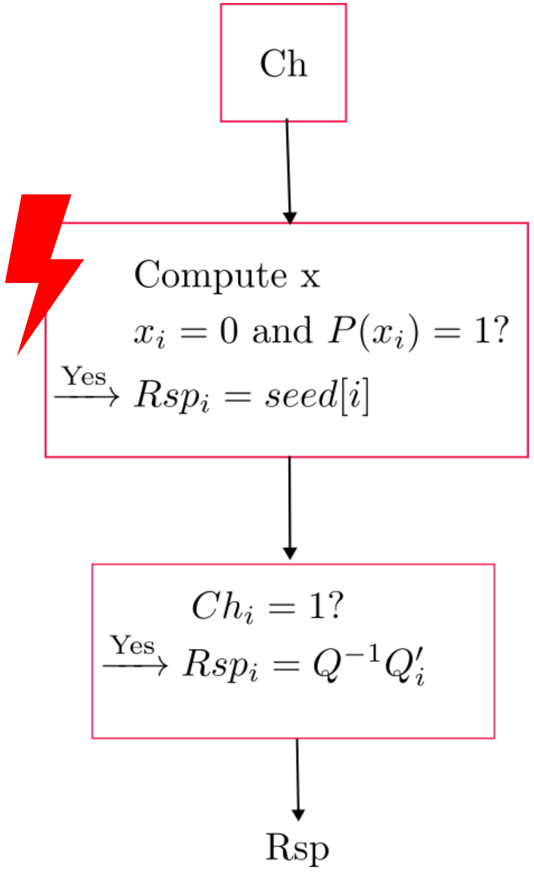
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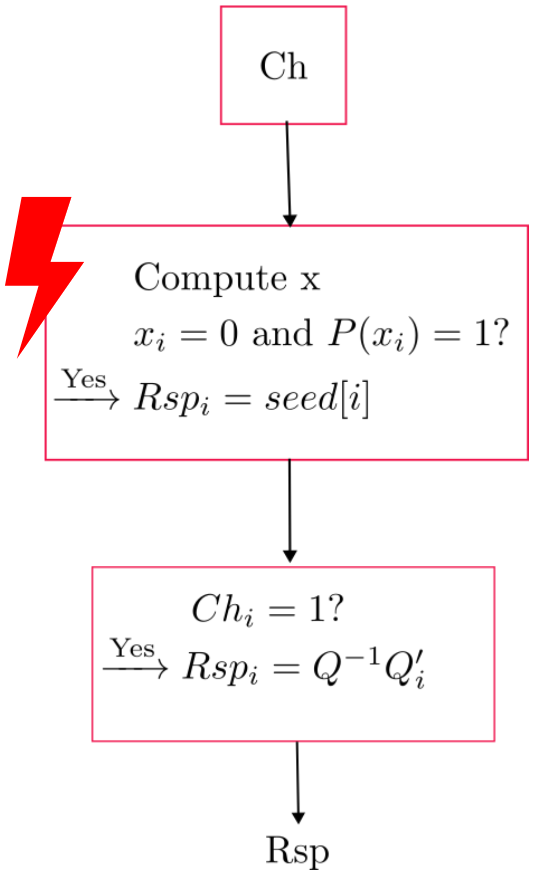
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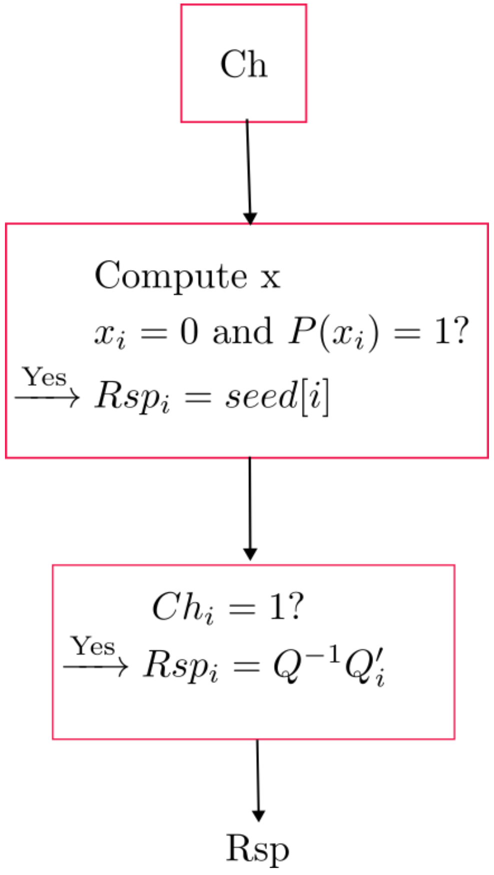
- The attack successfully done.

First Countermeasure



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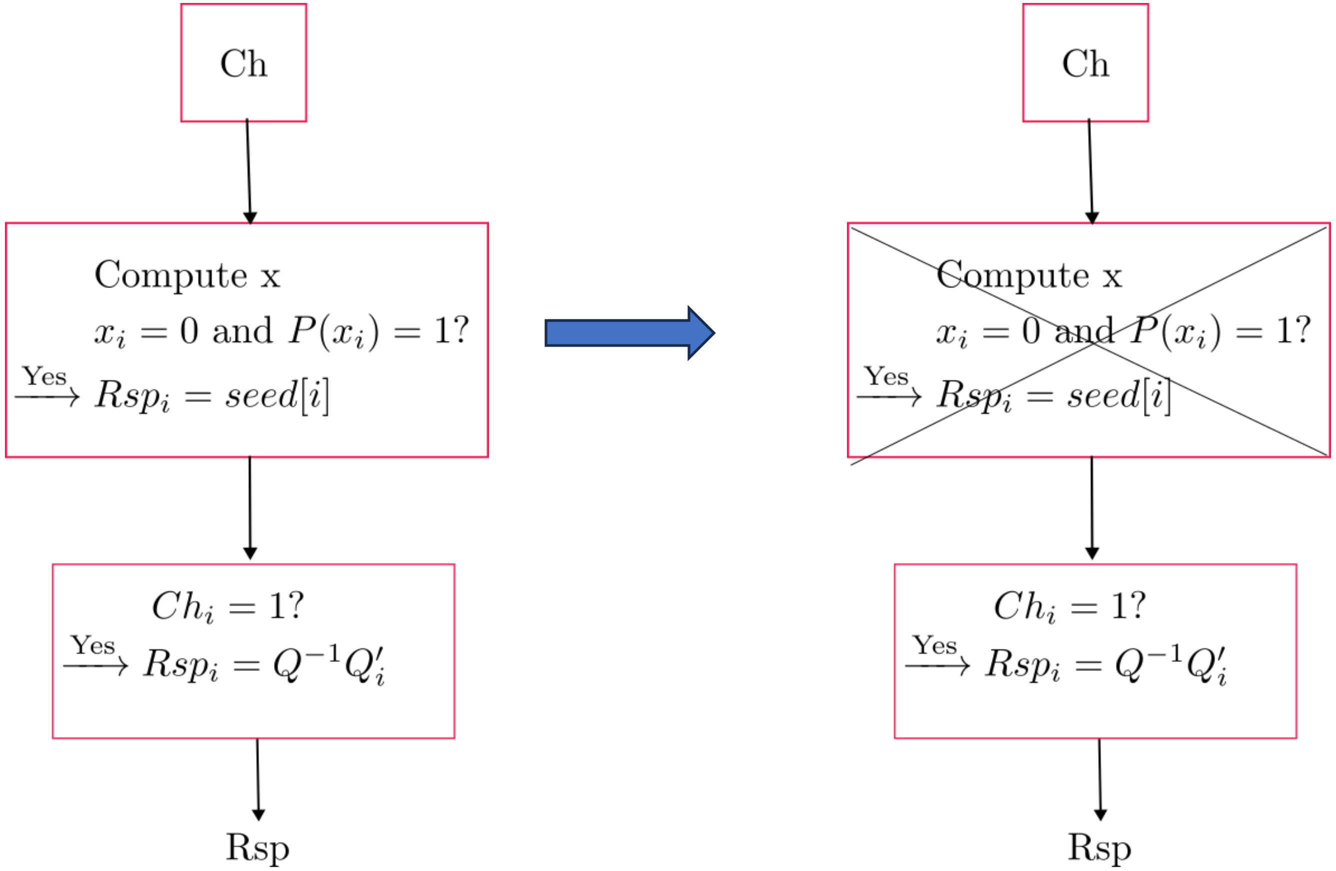

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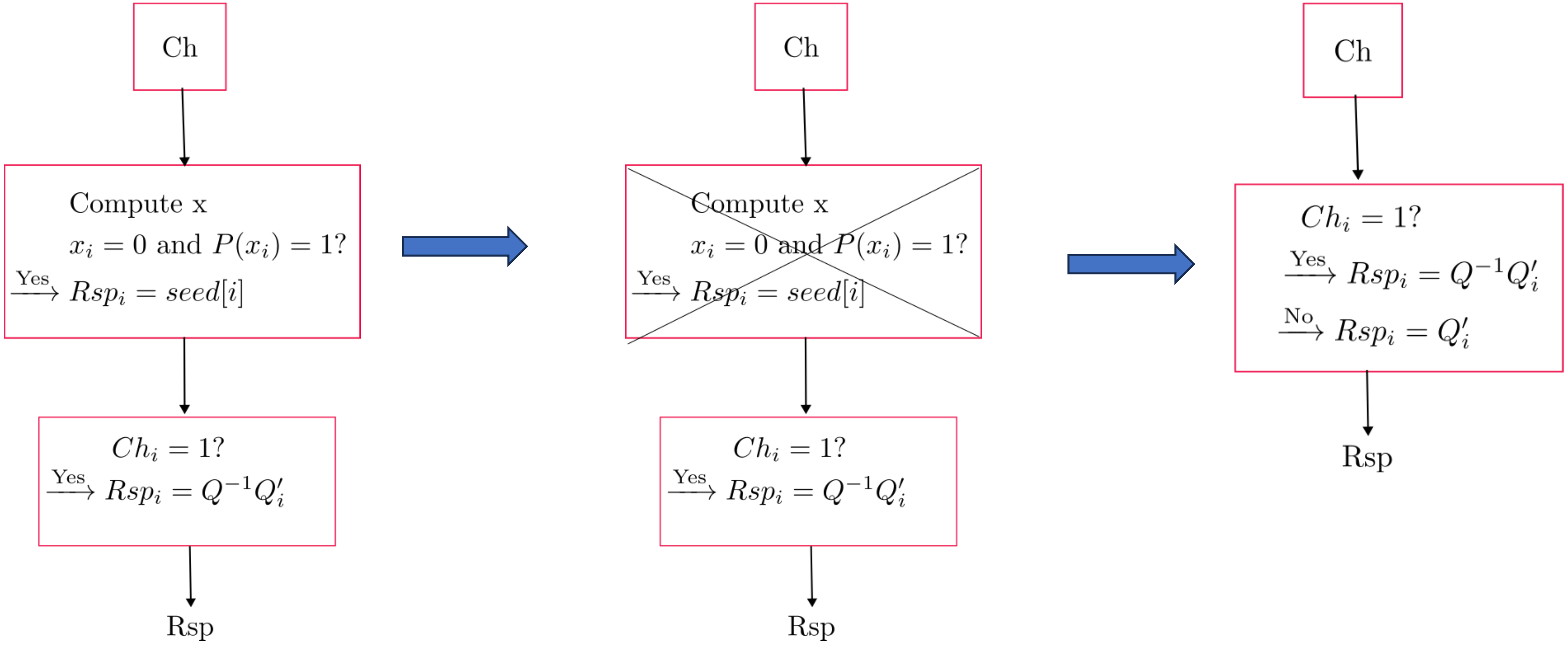

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Rsp

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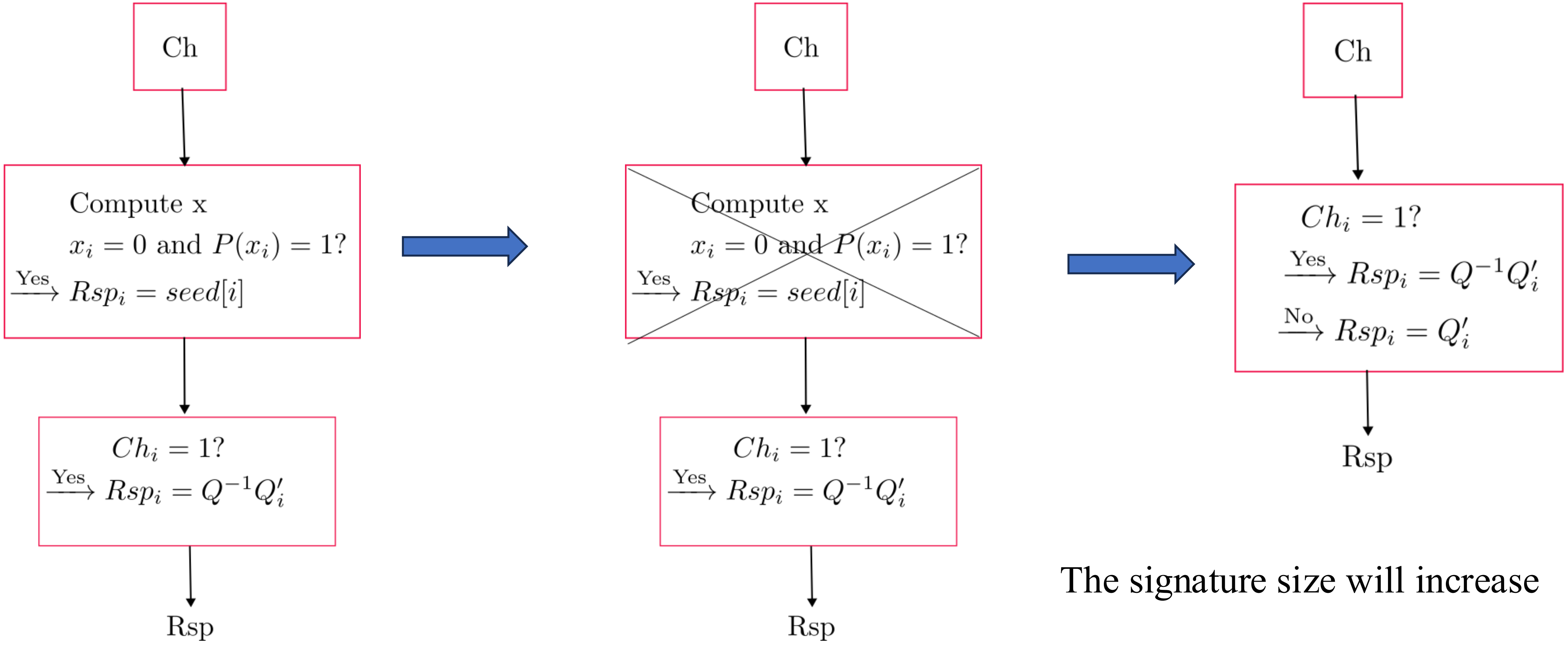

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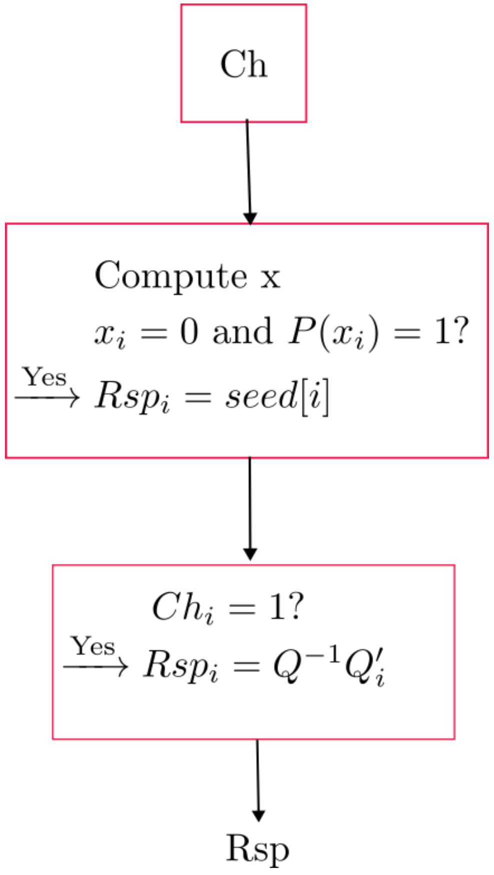
Rsp

The signature size will increase

Second Countermeasure



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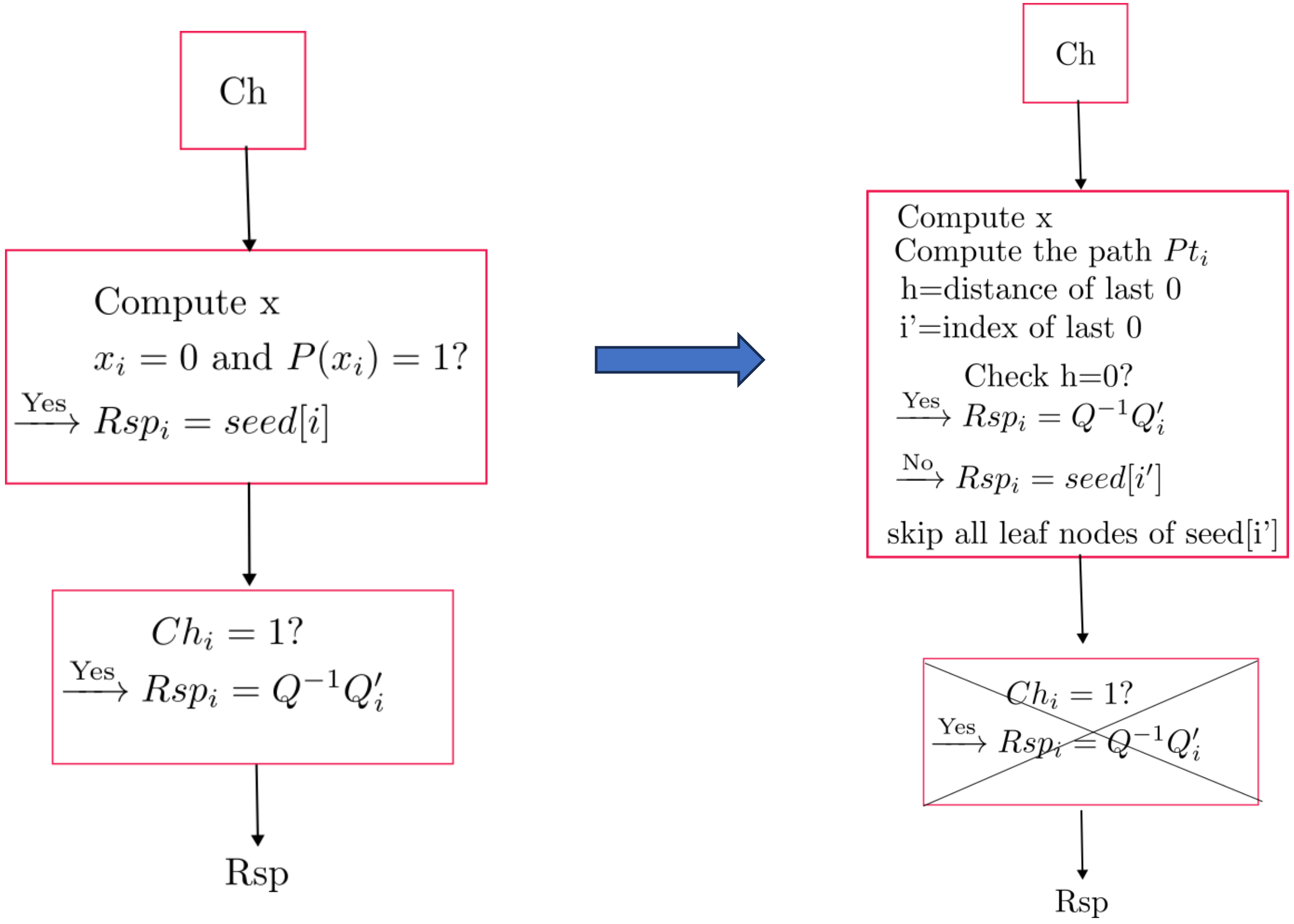

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Ch

Compute x
Compute the path Pt_i
h=distance of last 0
i'=index of last 0

Check h=0?

$\xrightarrow{\text{Yes}} Rsp_i = Q^{-1}Q'_i$

$\xrightarrow{\text{No}} Rsp_i = seed[i']$

skip all leaf nodes of seed[i']

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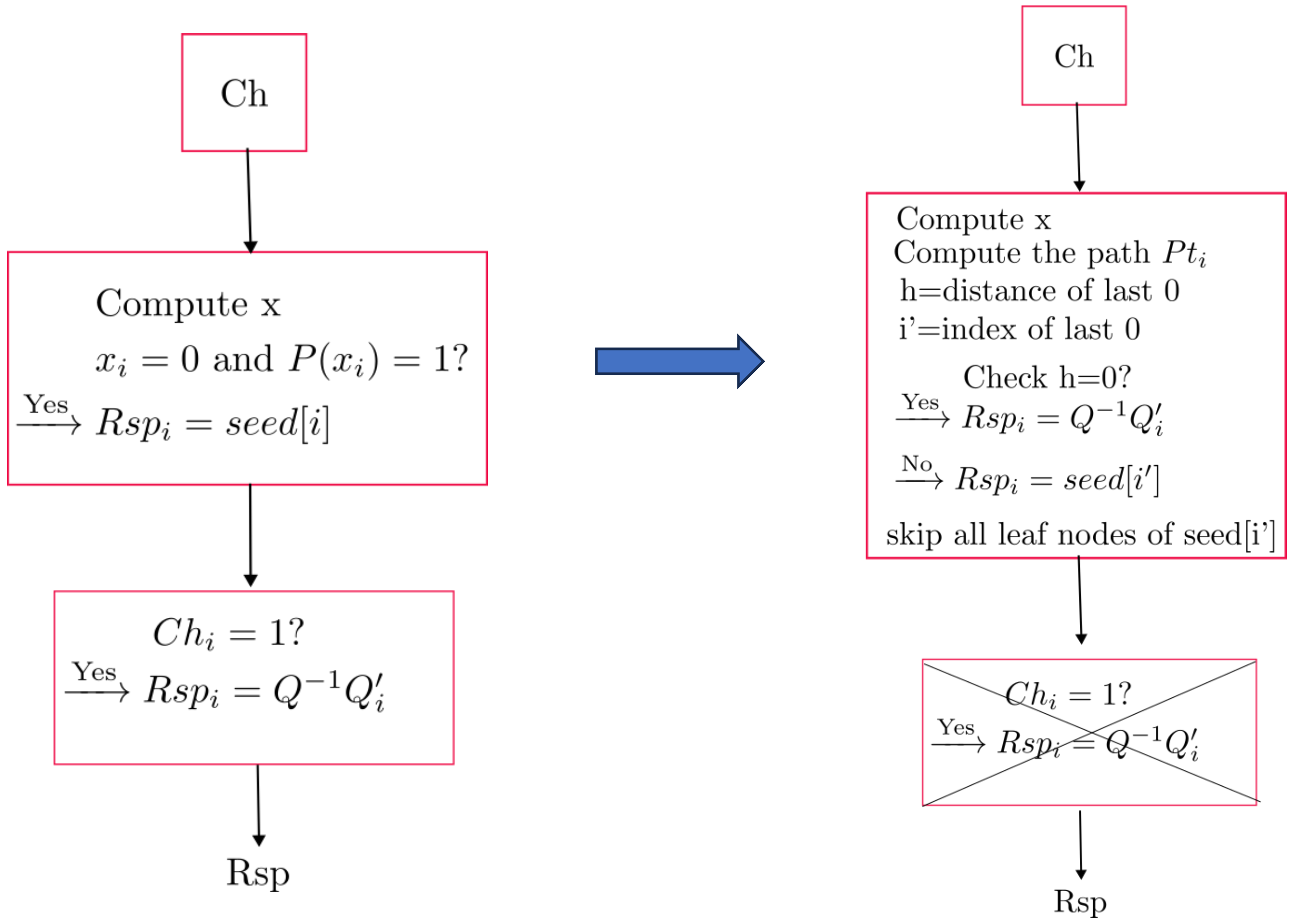

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- The signature size remain unchanged

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- It can be realized bit flip fault, struck at zero/one fault, instruction skip fault, etc.
- This attack can be applied to other schemes those uses the similar ZK structure
  - ✓E.g. MEDS
- We have proposed two countermeasures that prevent the fault

Questions?

Thank you!